

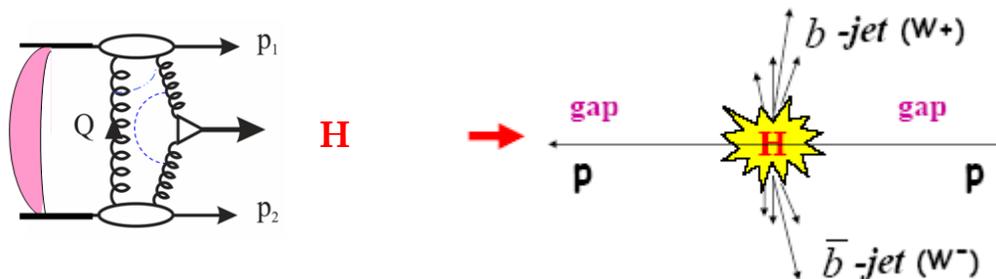


## Update on Exclusive Higgs Production



V.A. Khoze (IPPP, Durham)

(in collaboration with Lucian Harland-Lang and Misha Ryskin)



# Main Goal: **KEEP THE Ball ROLLING**



Current Status of CEP Theory

BY POPULAR  
DEMAND(Mike, Risto..)



# Forward Proton Taggers @ LHC as a gluonic Aladdin's Lamp

## • Higgs Studies

• Photon-Photon, Photon - Hadron Physics. 

• 'Threshold Scan': 'Light' New Physics ... 

• Various aspects of **Diffraction Physics** (*soft & hard*). 

• High intensity **Gluon Factory** (*undenatured gluons*) (~20 mln quarks vs 417 'tagged' g at LEP)

QCD test reactions, dijet PP-luminosity monitor 

**PRIOR TO THE LHC START-UP**

## FPT

★ Could provide a unique additional tool to complement the conventional strategies at the **LHC**.

$$\sigma(\text{CDPE}) \sim 10 * \sigma (\text{incl})$$

★ Higgs is only a part of the broad **EW, BSM** and diffractive program@LHC  
wealth of **QCD** studies, *glue-gluon collider, photon-hadron, photon-photon interactions...*

Current situation  
with 'diffractive Higgs'  
(post- LHC discovery)

We have to be open-eyed



+ strong evidence  
from the Tevatron

## Elusive particle found, looks like Higgs boson



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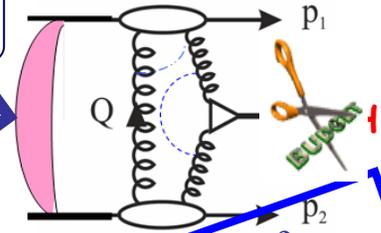


Rolf Heuer, Director-General of CERN, answers a journalist's question about the scientific seminar to deliver the latest update in the search for the Higgs boson in Meyrin near Geneva on Wednesday.

AP

# The main advantages of CEP Higgs production

- Prospects for high accuracy (~1%) mass measurement (irrespective of the decay mode). ☹️
- Quantum number filter/analyser. (0<sup>++</sup> dominance ; C,P-even)
- H → bb opens up (Hbb Yukawa coupl.) 😊  
(gg)CED ~~→~~ bb in LO ; NLO, NNLO, b-mass effects – controllable.
- For some BSM scenarios CEP may become a discovery channel ☹️



currently ATLAS FP-420  
(STFC cutting rule)  
CMS-HPS, Totem  
ATLAS-AFP

(very important feature)

- A handle on the overlap backgrounds- Fast Timing Detectors (10 ps timing or better). 🖱️

\* New leverage -proton momentum correlations (probes of QCD dynamics , CP- violation effects...) 🖱️

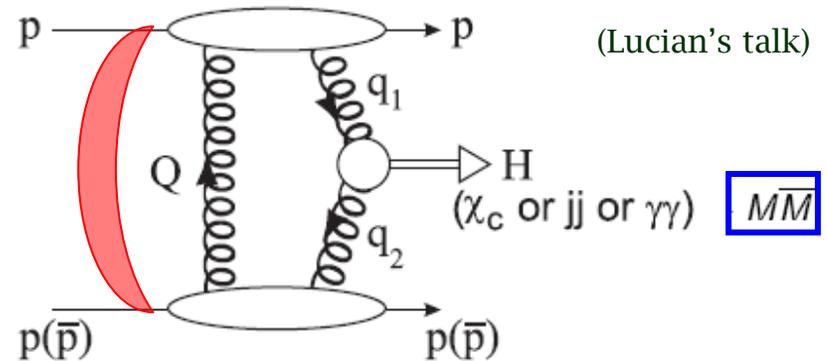
Triple product correlation:  $\vec{n}_0 \cdot (\vec{p}_{1\perp} \times \vec{p}_{2\perp}) \sim \sin \varphi$ ,

Integrated counting asymmetry (~10%)

$$A = \frac{\sigma(\varphi < \pi) - \sigma(\varphi > \pi)}{\sigma(\varphi < \pi) + \sigma(\varphi > \pi)}$$

# CEP through the eyes of the KRYSTHAL (2008-2013)

- Colliding protons interact via a colour singlet exchange and remain intact: can be measured by adding detectors far down the beam-pipe. (or LRGs)
- A system  $X$  of mass  $M_X$  is produced at the collision point, and *only* its decay products are present in the central detector.
- The generic process  $pp \rightarrow p + X + p$  is modeled perturbatively by the exchange of two t-channel gluons, with the use of pQCD justified by the presence of a hard scale  $\sim M_X$ .
- ‘ $J_z = 0$  selection rule’: production of states with non- $J_z^P = 0^+$  quantum numbers is strongly suppressed by  $\sim 2$  orders of magnitude.



- $\chi_c, \gamma\gamma$  CEP already observed by CDF and  $jj$  CEP observed by CDF & D0.
- $\chi_{cJ}$  CEP is reported by LHCb (DIS-11)
- new CDF  $\gamma\gamma$  CEP results (PRL-2012)
- All measurements in agreement with Durham group (pre)dictions.

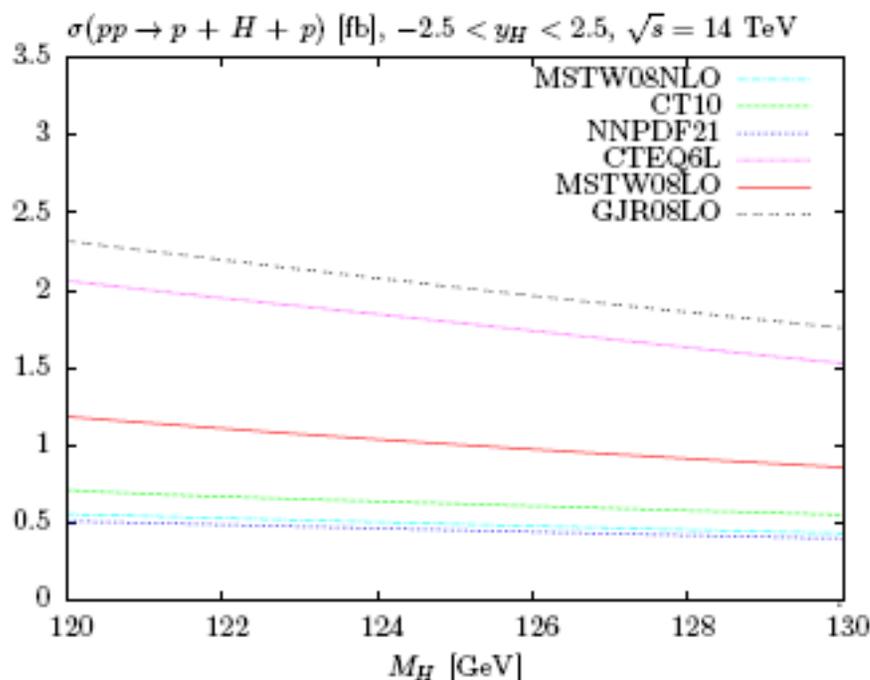
CMS--first CEP results, more to come

(LHCb-first inclusive  $\chi_{c0}$  mid-July 2013)

?

# Higgs Boson: cross section predictions

SuperCHIC



- Cross section  $\sim$  fbs, i.e. roughly 4 orders of mag. lower than inclusive case (price paid for exclusivity).
- Uncertainties (Survival factors, higher-order corrections, PDFs) exist in theoretical calculation. But  $\gamma\gamma$  CEP cross section tends to lie a little above theory estimates  $\rightarrow$  favours the higher predictions shown.

(MSSM update- Marek's talk)

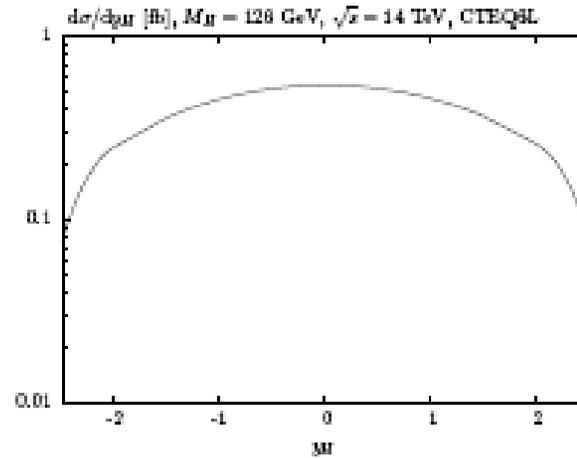


Figure 5: Rapidity distribution  $d\sigma/dy_H$  for a  $M_H = 126$  GeV SM Higgs boson, using CTEQ6L PDFs.

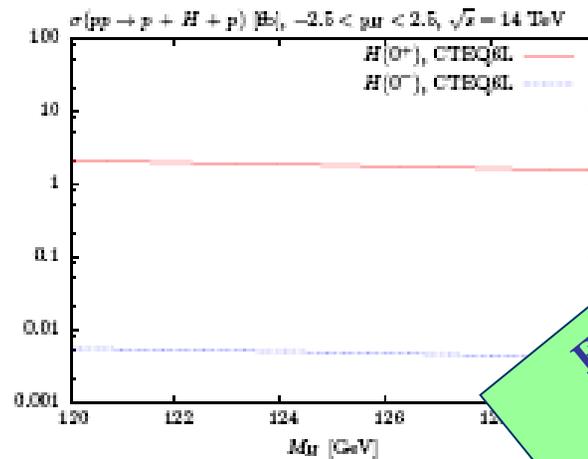


Figure 6: Cross sections for the CEP of scalar  $J^P = 0^+$  and pseudoscalar  $J^P = 0^-$  particles of the Higgs sector as a function of the Higgs mass,  $M_H$ , integrated over the rapidity interval  $-2.5 < y_H < 2.5$ .

**Find a CEP resonance and you have confirmed its quantum numbers!**



# New Durham Studies



(known unknowns)

- Account for the b-dependence of the survival factors

$$S_{\text{enh}}^2, S_{\text{eik}}^2$$

(KMR, GLM-new results)

- NLO effects in the unintegrated parton densities  
(N)NLO-effects in hard ME.



- A systematic account of self-energy insertions in the propagator of the screening gluon



- The dependence on the gluon PDF is amplified by the fact that the CEP cross section is essentially proportional to  $(xg(x))^4$ .

CDF  $\gamma\gamma$  data *may* suggest more 'LO-type' PDFs ( $\rightarrow$  more optimistic Higgs cross sections) are appropriate.



Improvements of models for soft diffraction: removing tensions with Totem data on  $\sigma_{\text{el}}$  and  $\sigma_{\text{tot}}$ , agreement with the LHC results on low mass SD, agreement with the Tevatron/LHC data on CEP processes subprogram to SuperCHIC to calculate  $S^2$  KRH-L

(KMR, arXiv:1306.2149)

SM Higgs, 125 GeV

## Signal-to-Background Ratio (a brief reminder)

$$H \rightarrow b\bar{b}$$

- ★ The largest signal, but large background and (most) difficult trigger  
(other channels -too low rate).
- ★ Major theor. uncertainties cancel in the ratio, in particular survival factors, PDFs,...
- ★ Experimental efficiencies (trigger, b-tagging..) cancel.

### Dominant non-PU backgrounds:

[DeRoeck, Orava+KMR, EPJC 25 (2002) 392, EPJC 53 (2008) 231]

- 1) Admixture of  $|J_z|=2$  production
- 2) NLO  $gg \rightarrow bbg$ , large-angle hard gluon emission
- 3) LO  $gg \rightarrow gg$ ,  $g$  can be misidentified as  $b$
- 4)  $b$ -quark mass effects in dijet processes, HO radiative corrections

Main characteristics:  
2007 (HKRTSW) values

}	Mass window	$\Delta M$	$\sim 4$ GeV.
	g-b misID	$P(g/b)$	$\sim 1.3\%$
	cone size	$\Delta R$	$\sim 0.5$ .

$$S/B \approx 1$$

(420+420)

Could be improved by a factor of 2 or so.

$b\bar{b}$  non-PU backgrounds

$$\sigma_B \simeq 2fb * (\Delta M / 4GeV) [A * (120GeV / M)^6 + 1/2 C_{NLO} * (120GeV / M)^8],$$

$$A \simeq 1/4 + 1/4 + 1/4 (P(g/b))^2,$$

$$C_{NLO} \simeq 0.48 - 0.12 * \ln(M / 120GeV).$$

- $P(g/b)$  1.3% → 1% (CMS)
- $\Delta M$  new detailed (post-2007) studies needed
- $\sigma_{bbg} / S \sim 20 * (\alpha_s C_F / 2\pi) * (\Delta R)^2 (\Delta M / 4GeV)$   
(requires detailed MC studies)

$$S / B \sim \Delta M / M^3$$

(ccg-similar)

The problem with pile-up  
How to trigger on low- $p_T$  jets?

**Experimental road-map:**

Andy Pilkington (CERN, Febr. 2013)

- (4) New cuts to reject the pile-up backgrounds will be necessary in order to extract a SM Higgs boson in the H → bb channel
- (5) Extensive work is needed to define the most appropriate trigger strategy for H → bb

## Most recent predictions

Harland-Lang, Khoze, Ryskin & Stirling: **0.5 to 2 fb**

[arXiv:1301.2552](https://arxiv.org/abs/1301.2552)

Depending on parton distribution functions. CTEQ6L gives upper value and provides best agreement with CDF di-photon data.  $S^2 = 1\%$  and  $|y| < 2.5$

Cudell, Dechambre, Hernández: **0.3 to 2 fb**

[arXiv:1011.3653](https://arxiv.org/abs/1011.3653)

'Our predictions are significantly lower than those of KMR'.  $S^2 = 5\%$  (?). Gluon constrained by CDF dijet data. **No Sudakov derivative**

Ryutin: **0.55 fb**

[arXiv:1211.2105](https://arxiv.org/abs/1211.2105)

$S^2 = 3\%$ .

**No Sudakov derivative**

Maciula, Pasechnik & Szczurek: **0.2 ~ 0.4 fb**

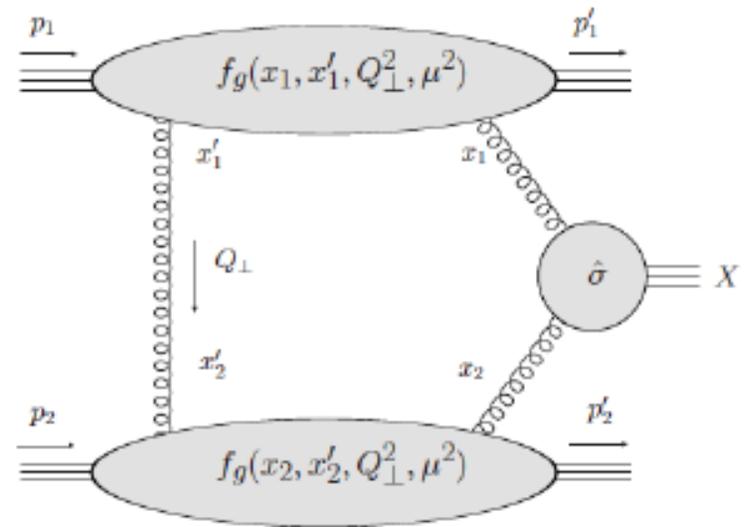
$S^2 = 3\%$ .

Higher scale in Sudakov

[arXiv:1011.5842](https://arxiv.org/abs/1011.5842)

**Rg outside**

Agreed uncertainty of a factor 3



$$\mathcal{M}(pp \rightarrow p + H + p) = A\pi^3 \int \frac{dQ_T^2}{Q_T^4} f_g(x_1, x'_1, Q_T^2, M_H^2/4) f_g(x_2, x'_2, Q_T^2, M_H^2/4) \quad (7)$$

where  $f_g(x, x', Q_T^2, M_H^2/4)$  denotes the skewed or off-diagonal unintegrated gluon density in the initial proton. The diagonal density is defined such that the probability to find a gluon (with transverse momentum  $Q_T$  and momentum fraction  $x$  in the interval  $dQ_T^2 dx$ ) is  $f_g(dQ_T^2/Q_T^2)(dx/x)$ . These unintegrated distributions are the quantities which enter when we apply the  $Q_T$ -factorization theorem [13] to the evaluation of the Feynman diagram of Fig. 1a. The procedure of how to calculate  $f_g(x, x, Q_T^2, \mu^2)$  from the conventional integrated gluon  $g(x, Q_T^2)$  is described in Ref. [14]. Here we will use the form proposed by DDT [15]

$$f_g(x, x, Q_T^2, \mu^2) = \frac{\partial}{\partial \ln Q_T^2} \left[ T(Q_T, \mu) xg(x, Q_T^2) \right], \quad (8)$$

where  $T(Q_T, \mu)$  is the survival probability that the gluon with  $x, x' = x$  and transverse momentum  $Q_T$  remains untouched in the evolution up to the hard scale  $\mu (= M_H/2)$ .  $T$  is the result of resumming the virtual ( $\propto \delta(1 - z)$ ) contributions in the DGLAP evolution equation and is given by [14]

$$T(Q_T, \mu) = \exp \left( - \int_{Q_T^2}^{\mu^2} \frac{\alpha_S(k_i^2)}{2\pi} \frac{dk_i^2}{k_i^2} \int \left[ zP_{gg}(z) + \sum_a P_{ga} \right] dz \right). \quad (9)$$

The derivative  $\partial T / \partial \ln Q_T^2$  in (8) cancels the virtual DGLAP term in  $\partial(xg) / \partial \ln Q_T^2$ . To be precise the equation for  $f_g$  is a little more complicated than (8) (see eq. (3) of [14]). However in the relevant small  $x$  and  $Q_T \ll M_H$  region, (8) is sufficiently accurate for our purposes. Note that after integrating (8) up to scale  $\mu$  we do indeed get back the integrated gluon distribution

$$\int^{\mu^2} f_g(x, x, Q_T^2, \mu^2) \frac{dQ_T^2}{Q_T^2} = T(\mu, \mu) xg(x, \mu^2) = xg(x, \mu^2). \quad (10)$$

1. The pQCD part of the calculation is under “reasonable” control (off-diagonal gluon uncertainty dominates).



2. Need a good model of factorization breaking exchanges (a.k.a. gap survival). Central production of other high-mass systems (**di-photons & dijets**) will really help us to understand it.

(nowadays GLM and KMR are in a broad agreement on survival)

3. Correct treatment of Sudakov and TOTEM data pull cross section down. (taken into account in SuperCHIC)

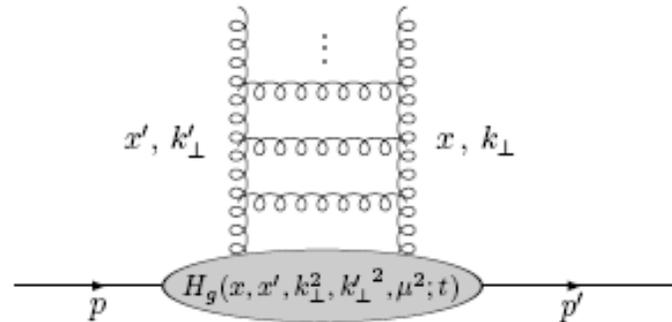
4. Higher order corrections and CDF data push cross section up. (in progress)

5. Nobody is claiming a cross section above 2 fb.



# Off-diagonal partons (1)

- The CEP cross section is given in terms of 'off-diagonal' PDF, unintegrated over the gluon  $k_{\perp}$ : corresponds to extraction of 2-gluon state from proton. For CEP have



$$f_g(x, x', Q^2, \mu^2) = \frac{\partial}{\partial \ln(Q_{\perp}^2)} \left[ R_g(xg(x, Q^2)) \sqrt{T(Q_{\perp}, m_H)} \right].$$

KMR(2000)- an extension of the results by DDT(1980) (ignored by some authors of the recent papers)

- $R_g = H_g(x, x'; \mu^2)/xg(x, \mu^2)$ : ratio of off-diagonal to conventional integrated gluon PDF. Can be calculated from [Shuvaev transform](#), which relates conventional to off-diagonal PDFs at small  $x$ . Valid up to corrections of  $O(x^2, x'^2)$ .
  - In CEP kinematics momentum fraction of screening gluon  $x' \ll x$  and  $x \sim M_X/\sqrt{s} \ll 1$ .
- Off-diagonal gluon density can be calculated to very good  $\lesssim 1\%$  accuracy from conventional gluon, and does not represent an important source of theoretical uncertainty.

## Off-diagonal partons (2)

- Often the approximation is made

$$f_g(x, x', Q^2, \mu^2) \approx R_g \frac{\partial}{\partial \ln(Q_{\perp}^2)} \left[ xg(x, Q^2) \sqrt{T(Q_{\perp}, m_H)} \right], \quad (1)$$

ignoring the scale dependence of  $R_g$ , i.e. assuming the off-diagonal and conventional PDFs have the same evolution with scale  $\mu$ .

- **However** only approximately true, and as  $\sigma_{\text{CEP}} \sim (f_g)^4$ , care is needed.
- A more careful treatment, including  $R_g$  inside the differential, shows that for Higgs CEP at the LHC ( $M_h = 126$  GeV,  $\sqrt{s} = 14$  TeV), this can underestimate the cross section by up to a factor of  $\sim 2$ . Table: cross sections in fb, with  $R_g$  inside and outside differential (1).
- Latest Durham predictions ([arXiv:1301.2552](https://arxiv.org/abs/1301.2552)) are consistent with this correct treatment.

	MSTW08LO	CTEQ6L	GJR08LO
$\sigma/\text{fb}, R_g$ Outside	0.83	1.15	1.94
$\sigma/\text{fb}, R_g$ Inside	1.39	1.91	2.66

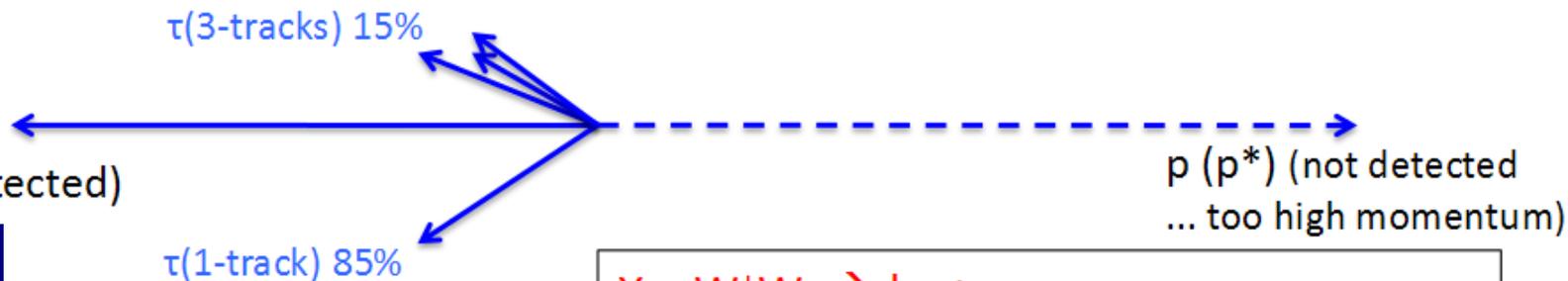
## One proton measured, still some physics at high PU?:

High mass diffraction well explored in  $\sim 1$  week of  $\mu = \langle n/x \rangle \sim 1$  running  $\sim 100/\text{pb}$ .

$M(\text{min}) \sim 100 \text{ GeV}$ .

No  $M(X)$  from p's, no PH rejection by timing, but very clean central states may be accessible

E.g.



$X = W^+W^- \rightarrow \text{leptons}$

$X = e^+e^-, \mu^+\mu^-, \tau^+\tau^-$  from  $\gamma\gamma$  (or H !?)

$X = Z$  photoproduction  $\rightarrow e^+e^-, \mu^+\mu^-, \tau^+\tau^-$

No additional tracks on X vertex (already very selective)

In  $e^+e^-, \mu^+\mu^-, \tau^+\tau^-$  cases  $\Delta\phi = \pi$  and  $p_T(X) \sim 0$ .

**Can we see  $p + [H125 \rightarrow \tau^+\tau^-] + p^*(\text{undetected})$  in Stage 1 ??**

(Study with Harland-Lang, Khoze, Ryskin)

3-momentum of X ( $\sim p_z$ ) determines both proton momenta

$e^+e^-, \mu^+\mu^-$  already calibrates HPS spectrometers (don't need both p's)

## Can we see H(125) in Stage 1 with one proton?

Exclusive  $p + \tau^+\tau^- + p$  (clean) :

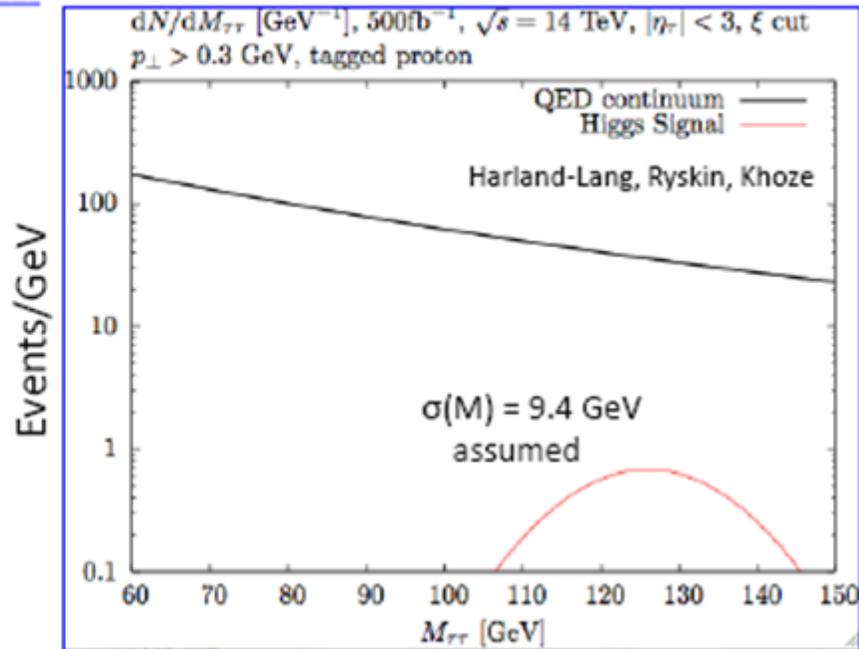
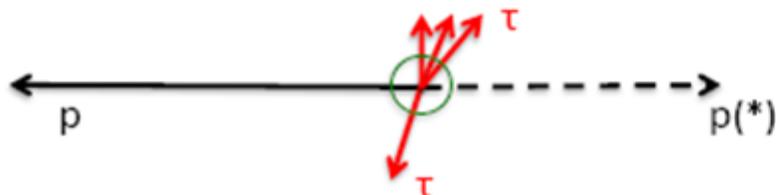
Only 3 sources:

1) QED:  $\gamma\gamma \rightarrow \tau^+\tau^-$

2) Photoproduction:  $\gamma+IP \rightarrow Z$  (BR = 3.7%)

3) Gluon fusion  $IP + IP \rightarrow H$  (BR = 6%)

1<sup>st</sup> two same in  $e+e-$  and  $\mu+\mu-$  (control)



Two neutrinos missing, but 4-momentum constraints & two  $M(\tau)$  constraints.

a) If fully optimised, how good can  $M(\tau^+\tau^-)$  be?

Factor x2 better  $\sigma(M) \rightarrow$  factor x2 peak height and in S:B. (possible??)

b) QED continuum,  $\gamma\gamma \rightarrow \tau^+\tau^-$ ,  $p_T(p) < p_T(p)$  in  $H \rightarrow \tau^+\tau^-$  (gluons, or IP)

$p_T > 0.3$  GeV cut (as in plot) reduces QED by factor  $\sim 5$ , only 10% reduction in H.

c) Unseen low mass  $p$ -dissociation on other side increases  $\sigma$ , factor  $\sim 2$ (?) without spoiling kinematics.  $\sigma(H)$  also uncertain by a factor  $\sim 2-3$  each way.

Still,  $SMH(125) \rightarrow p + \tau^+\tau^- + p^*$  probably too small to see in Stage 1.

>> at Stage 2 with 420+240 have other  $p$ , better mass resolution, & timing for  $z(vtx)$  constraint. :-)

# Low $M_H$ MSSM scenario

(see for instance arXiv: 1302.7033, also NMSSM)

- The LHC signal corresponds to the heavy CP-even Higgs boson.- SM like.
- Light CP-even Higgs - heavily suppressed couplings to the gauge bosons.
- The available parameter space is already affected by the current limits.
- All 5 Higgs states have masses have masses of order 100 GeV
- Rich phenomenology- but might be excluded by the standard search channels at the LHC comparatively soon.
- Recall also that the background is increasing with mass decreasing



$$S/B \sim \Delta M / M^3$$

(Marek's talk)

(New studies in progress by M.Tasevsky, S.Heinemeyer, G.Weiglein and VAK)

THANK  
YOU



QUESTIONS?



*Jury is still out*



*BACKUP*



A MC event generator including<sup>8</sup>:

- Simulation of different CEP processes, including all spin correlations:
    - $\chi_{c(0,1,2)}$  CEP via the  $\chi_c \rightarrow J/\psi\gamma \rightarrow \mu^+\mu^-\gamma$  decay chain.
    - $\chi_{b(0,1,2)}$  CEP via the equivalent  $\chi_b \rightarrow \Upsilon\gamma \rightarrow \mu^+\mu^-\gamma$  decay chain.
    - $\chi_{(b,c)J}$  and  $\eta_{(b,c)}$  CEP via general two body decay channels
    - Physical proton kinematics + survival effects for quarkonium CEP at RHIC.
    - Exclusive  $J/\psi$  and  $\Upsilon$  photoproduction.
    - $\gamma\gamma$  CEP.
    - Meson pair ( $\pi\pi$ ,  $KK$ ,  $\eta\eta\dots$ ) CEP.
  - More to come (dijets, open heavy quark, **Higgs** ).
- Via close collaboration with CDF, STAR and LHC collaborations, in both proposals for new measurements and applications of SuperCHIC, it is becoming an important tool for current and future CEP studies.

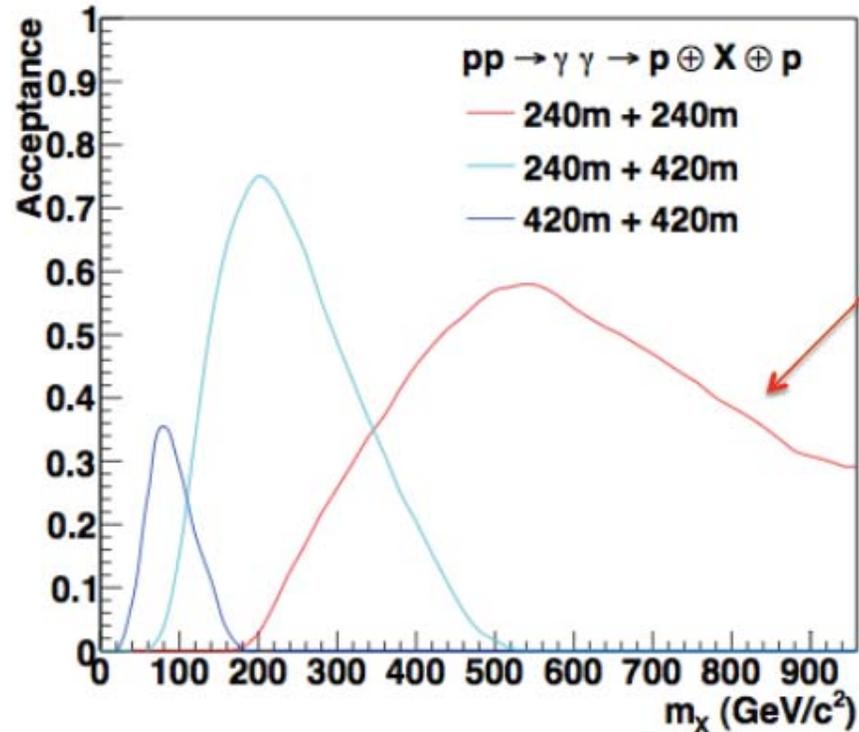
subprogram for  $S^2$

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<sup>8</sup>The SuperCHIC code and documentation are available at <http://projects.hepforge.org/superchic/>



## Mass acceptance for two arms for small $|t|$ at Stations 1 & 2 (Assumes $\Delta x(\text{min})$ from beam = 3 mm at 240m)



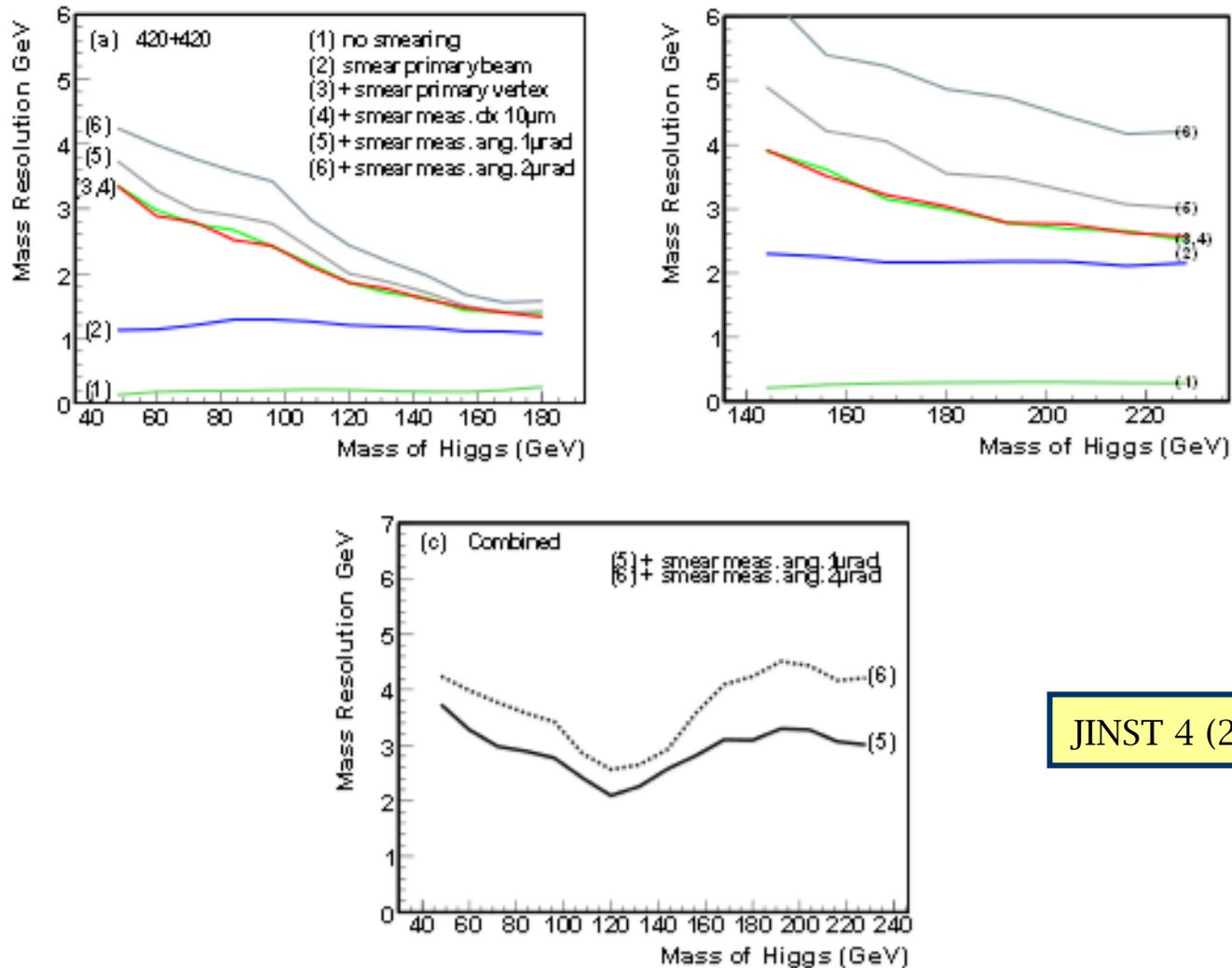
Stage 1: very good for  
W+W- and Jet+Jet and  
BSMH(400-800)



Each arm at 240m by itself has  $\sim$  superimposed light blue and red.  
Stage 2 has  $\sim$  all 3 superimposed, and light blue x 2.

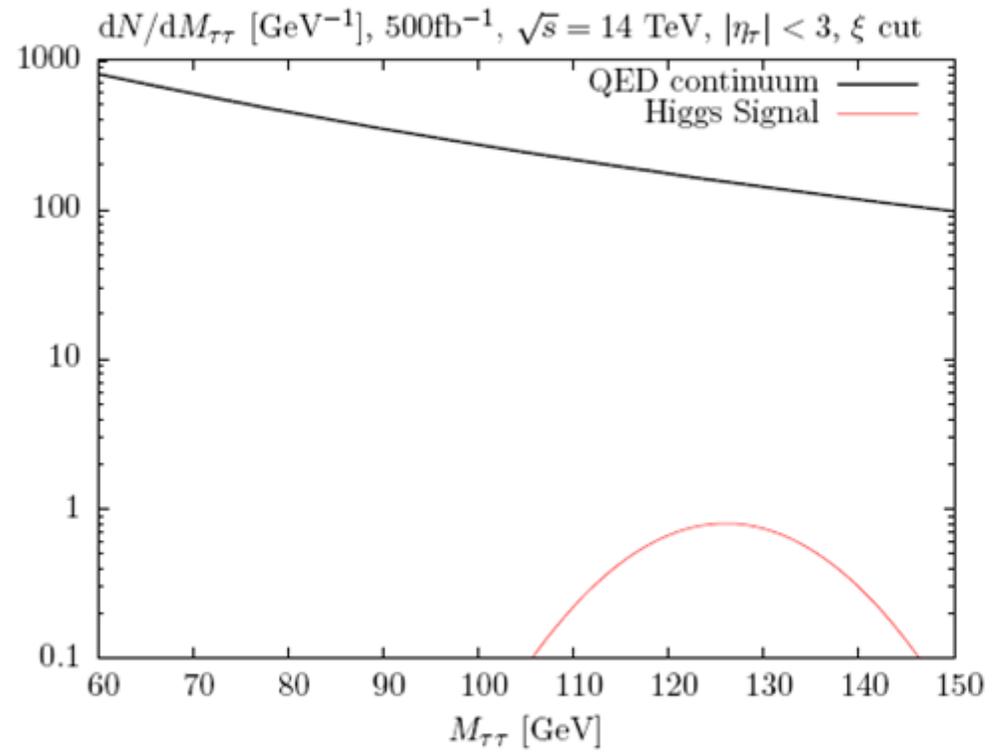
For IP + IP  $|t|$  is larger and acceptance shifts.

For H(125) best is [240 + 420] & [420 + 240]



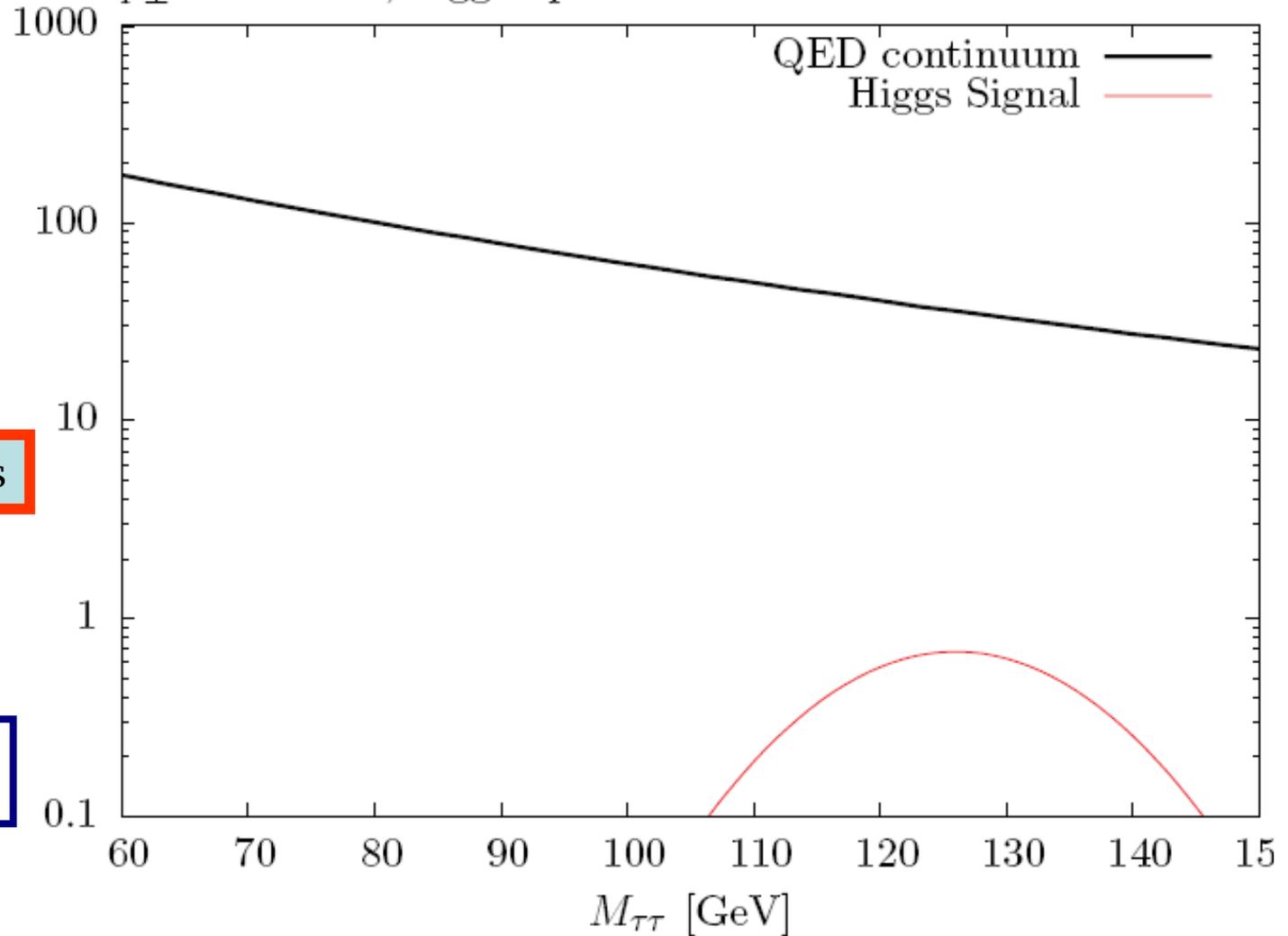
JINST 4 (2009) T10001

Fig. 32: Mass resolutions obtainable in ATLAS (a) for 420 + 420 m measurements, (b) for 420 + 220 m measurements, (c) combined. The curves have different amounts of smearing applied as explained in the text.





$dN/dM_{\tau\tau}$  [ $\text{GeV}^{-1}$ ],  $500\text{fb}^{-1}$ ,  $\sqrt{s} = 14 \text{ TeV}$ ,  $|\eta_{\tau}| < 3$ ,  $\xi$  cut  
 $p_{\perp} > 0.3 \text{ GeV}$ , tagged proton



~20 signal events

S/B may improve by a factor of ~2