Title: Fully exploring exotic production of the 125 GeV Higgs

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Abstract: I consider the effects of exotic production modes of the 125 GeV Higgs and their impact on Higgs searches and the Higgs discovery. I emphasize that new production modes have been largely overlooked in contemporary tests of the Standard Model nature of the Higgs boson but experimental tests of exotic production modes are viable now or will be soon. I present a couple explicit examples of exotic production arising from chargino-neutralino associated production in the MSSM. As a corollary of this work, I point out that current Higgs coupling fits do not adequately explore the complete space of new physics deviations possible in Higgs measurements.

FULLY EXPLORING EXOTIC PRODUCTION OF THE 125 GEV HIGGS

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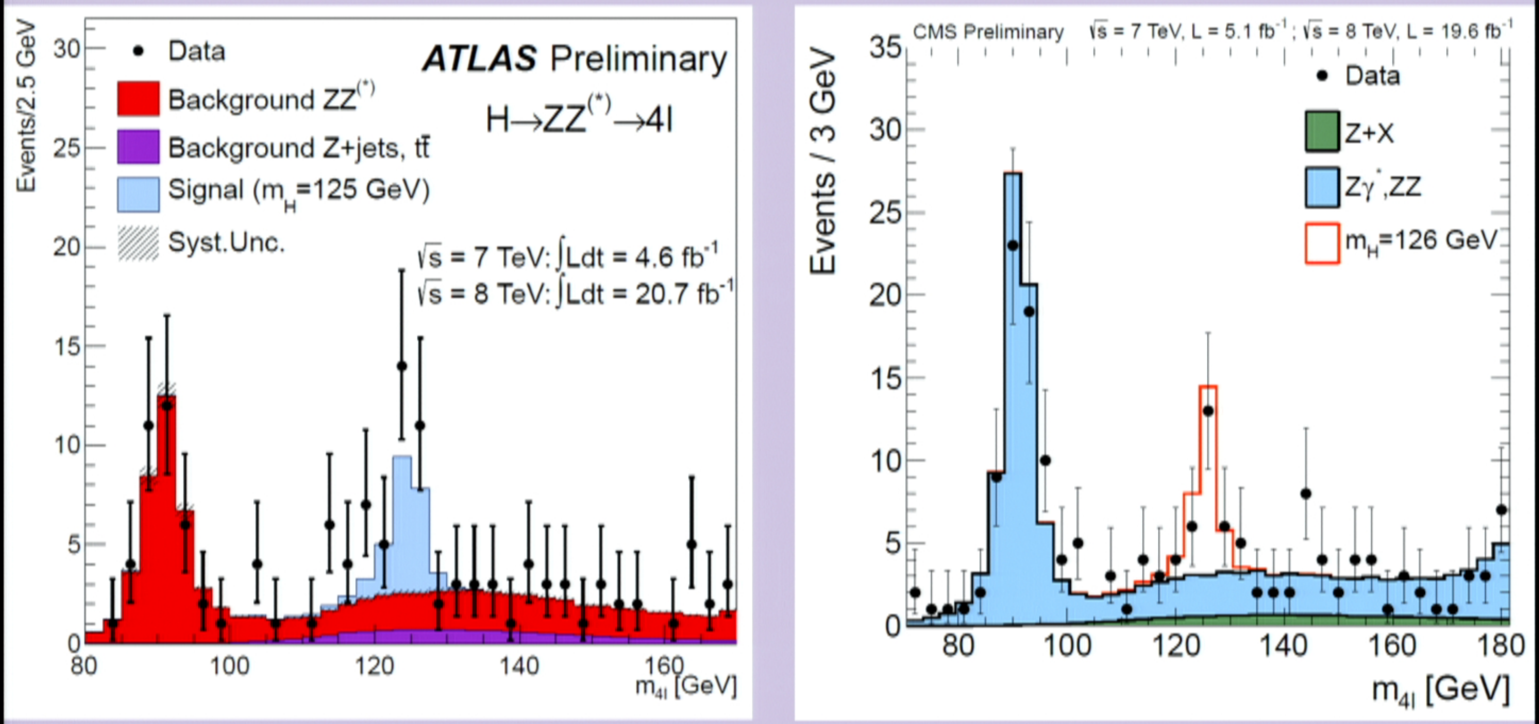
[arXiv:1312.xxxx]

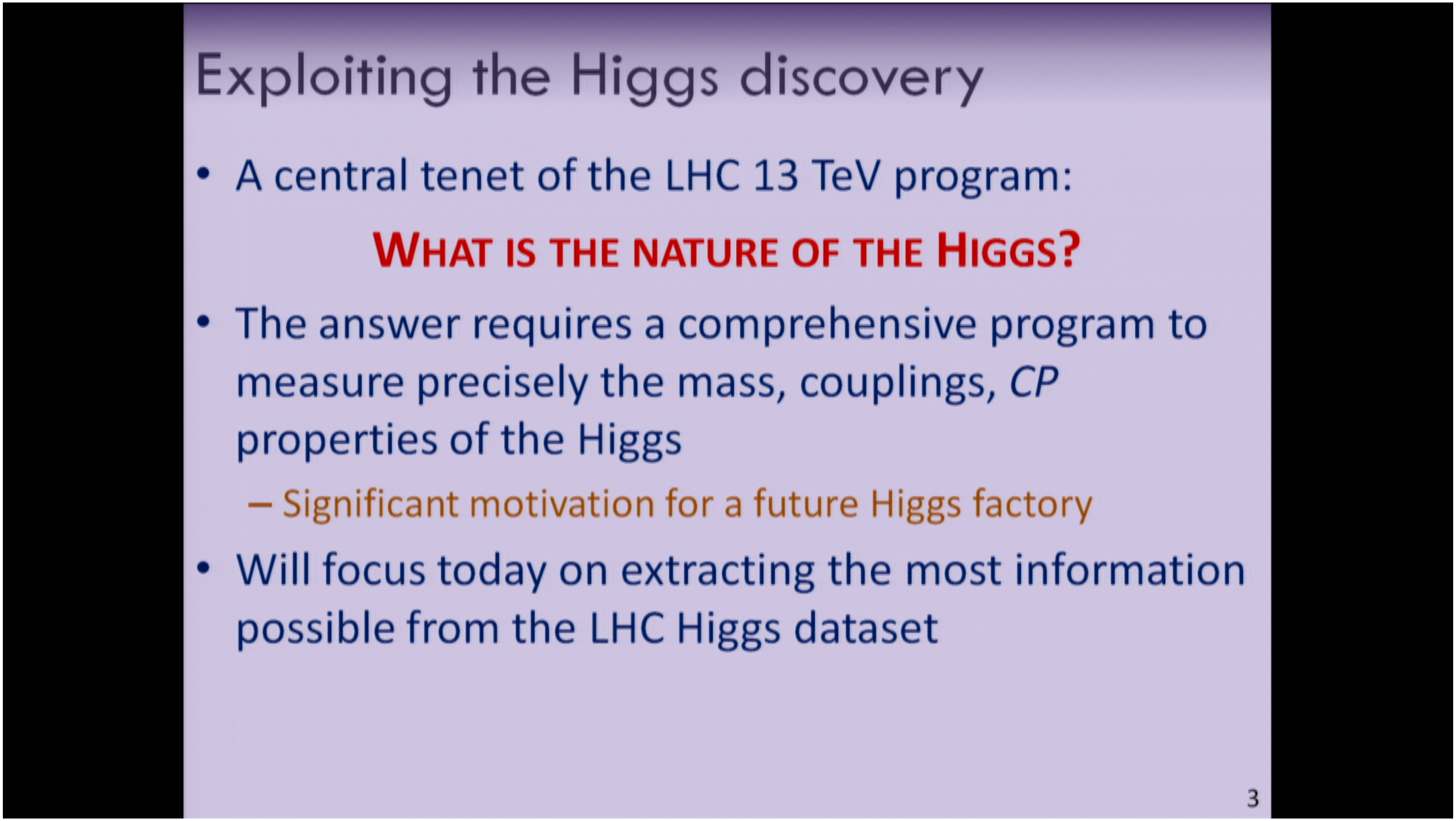
Particle Physics Seminar, Perimeter Institute
December 3, 2013

Higgs discovery



– The completion of the Standard Model sharpens the gauge hierarchy problem

ATLAS-CONF-2013-013, CMS HIG-13-002



Exploiting the Higgs discovery

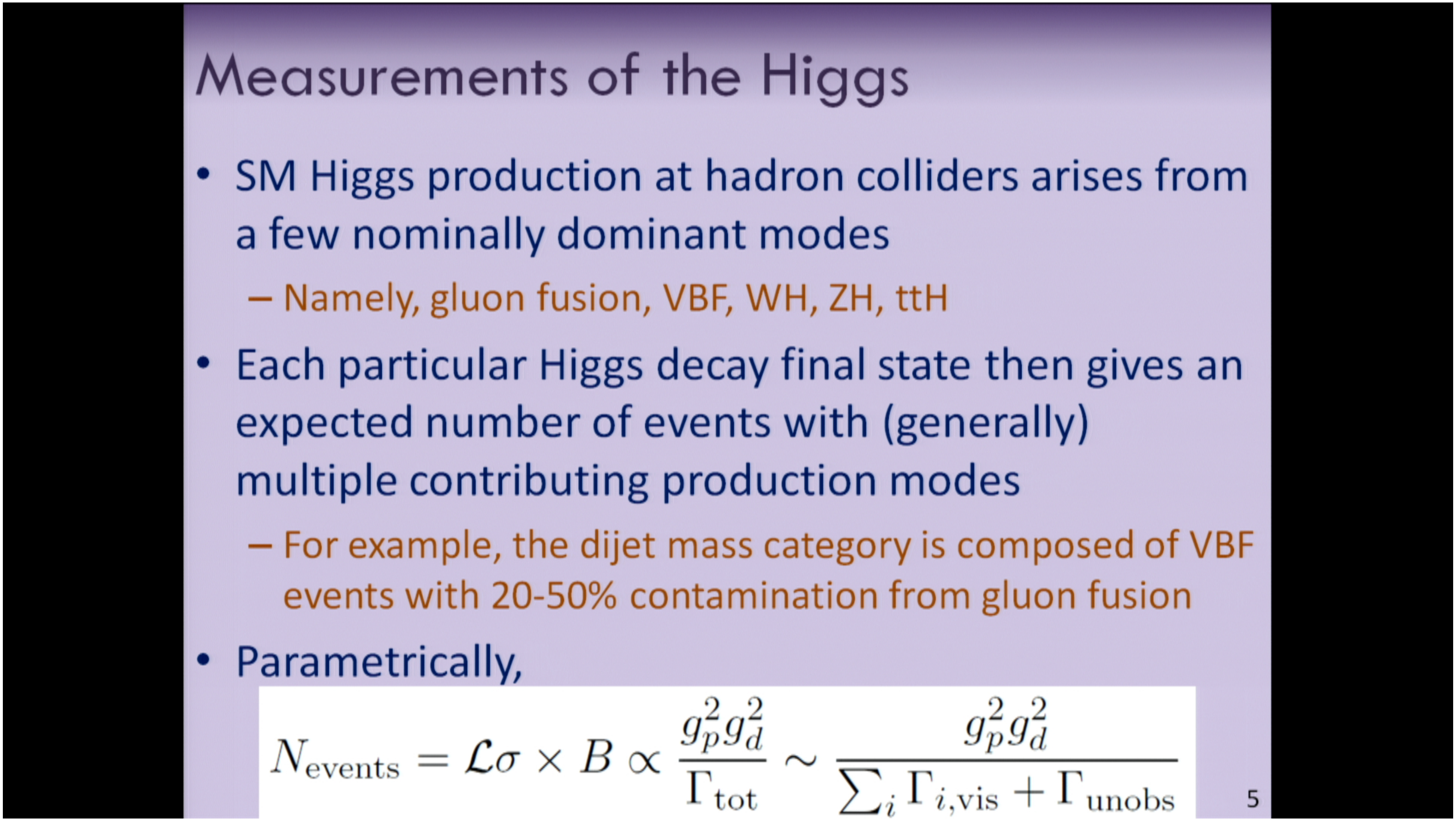
- A central tenet of the LHC 13 TeV program:

WHAT IS THE NATURE OF THE HIGGS?

- The answer requires a comprehensive program to measure precisely the mass, couplings, *CP* properties of the Higgs
  - Significant motivation for a future Higgs factory
- Will focus today on extracting the most information possible from the LHC Higgs dataset

Outline

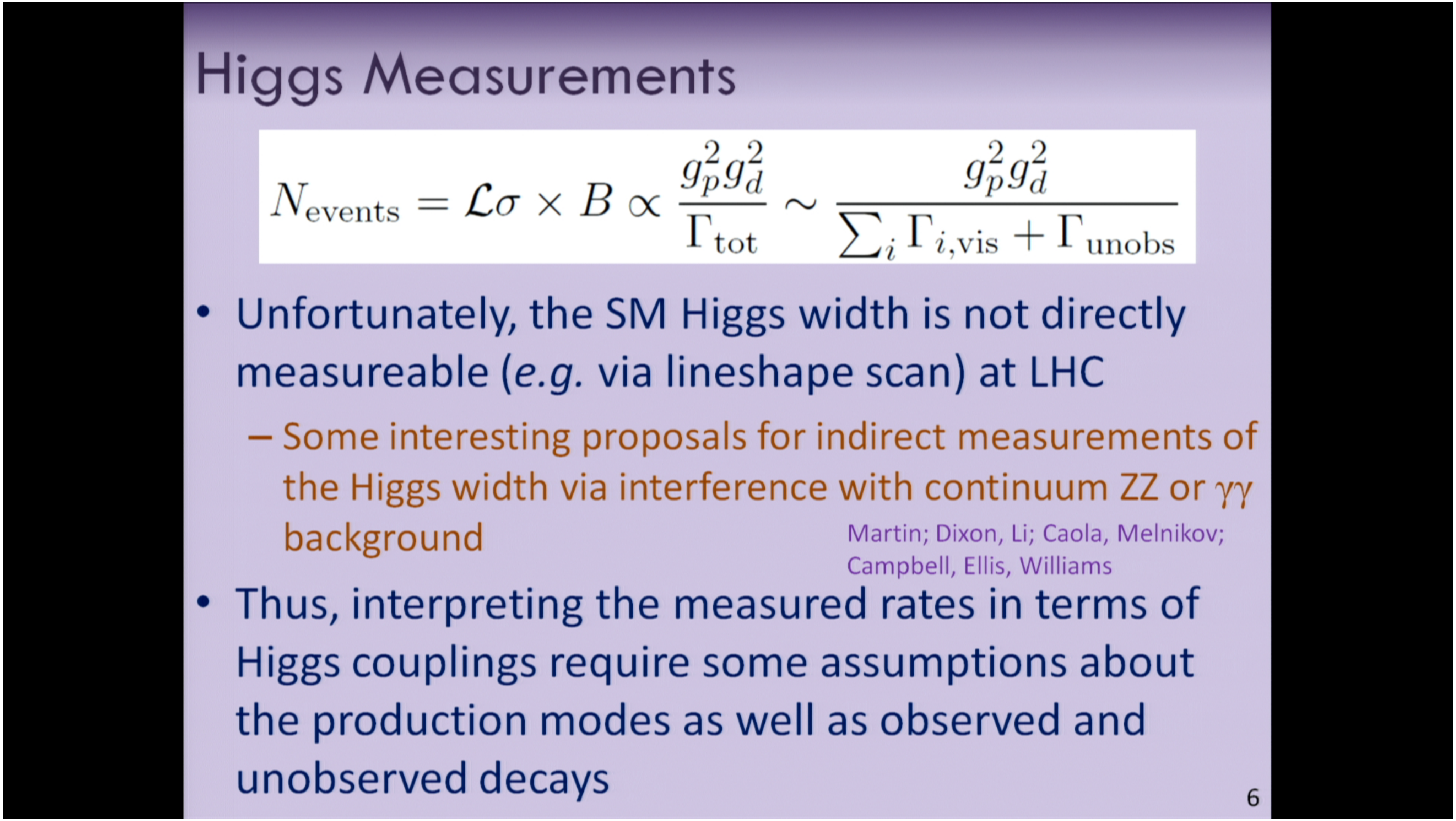
- Review current Higgs studies
- Possible scenarios of exotic Higgs production
- Specific case: chargino-neutralino production
    - Current constraints and usual searches
    - Effects on SM Higgs analysis
- Proposed probes of exotic production
- Summary



Measurements of the Higgs

- SM Higgs production at hadron colliders arises from a few nominally dominant modes
  - Namely, gluon fusion, VBF, WH, ZH, ttH
- Each particular Higgs decay final state then gives an expected number of events with (generally) multiple contributing production modes
  - For example, the dijet mass category is composed of VBF events with 20-50% contamination from gluon fusion
- Parametrically,

$$N_{\text{events}} = \mathcal{L}\sigma \times B \propto \frac{g_p^2 g_d^2}{\Gamma_{\text{tot}}} \sim \frac{g_p^2 g_d^2}{\sum_i \Gamma_{i,\text{vis}} + \Gamma_{\text{unobs}}}$$



Higgs Measurements

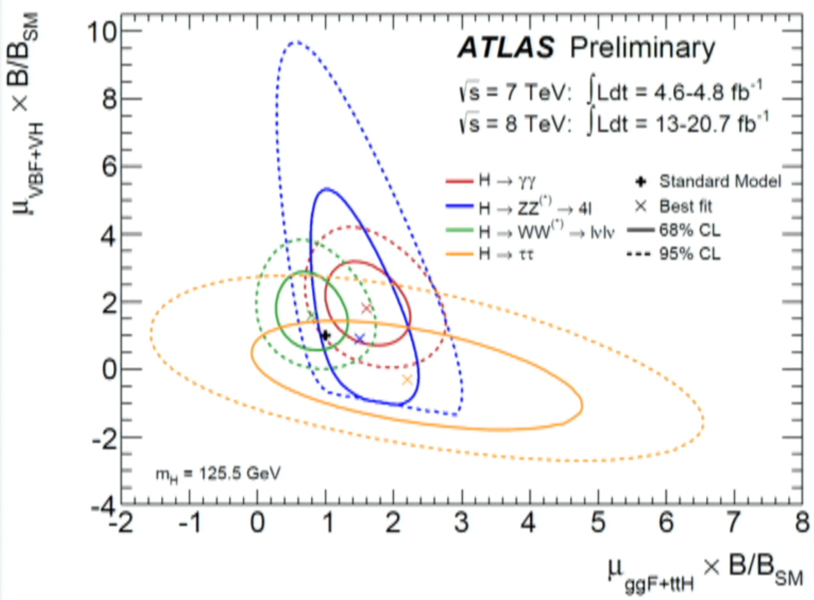
$$N_{\text{events}} = \mathcal{L}\sigma \times B \propto \frac{g_p^2 g_d^2}{\Gamma_{\text{tot}}} \sim \frac{g_p^2 g_d^2}{\sum_i \Gamma_{i,\text{vis}} + \Gamma_{\text{unobs}}}$$

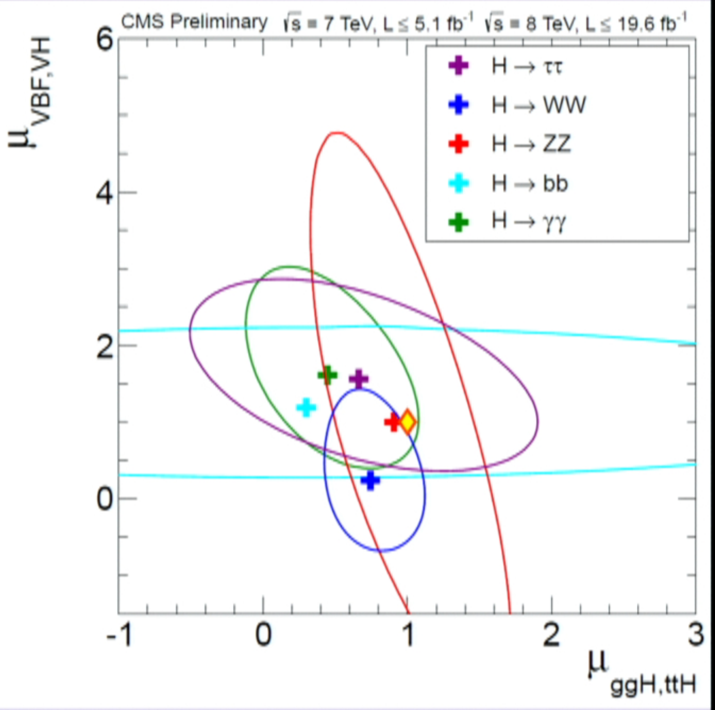
- Unfortunately, the SM Higgs width is not directly measureable (*e.g.* via lineshape scan) at LHC
  - Some interesting proposals for indirect measurements of the Higgs width via interference with continuum ZZ or $\gamma\gamma$ background

Martin; Dixon, Li; Caola, Melnikov; Campbell, Ellis, Williams

- Thus, interpreting the measured rates in terms of Higgs couplings require some assumptions about the production modes as well as observed and unobserved decays

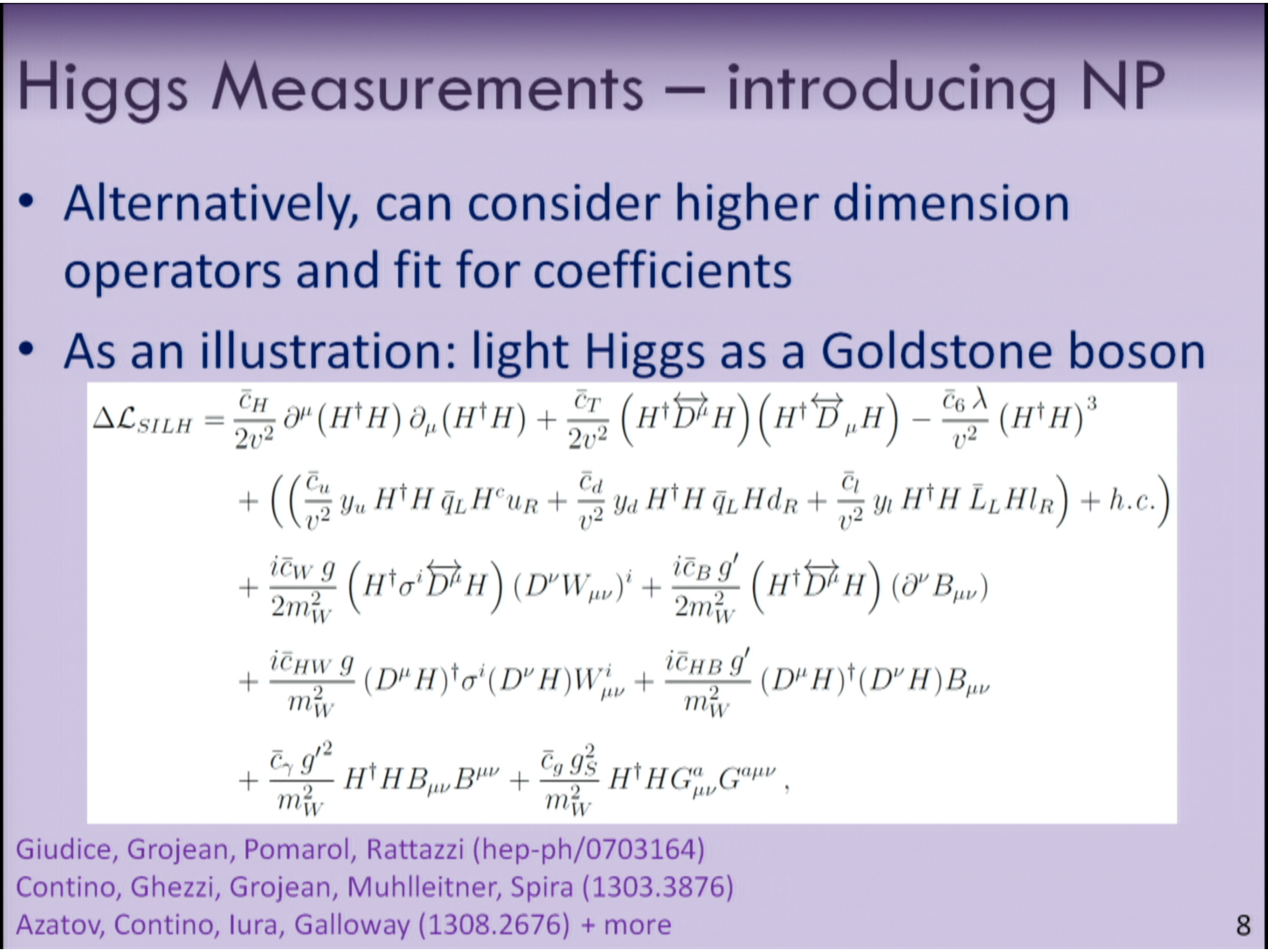
Higgs Measurements





- Signal strength defined as $\mu_i = \sigma_i/\sigma_{i,\mathrm{SM}}$

ATLAS-CONF-2013-034, CMS PAS HIG-13-005

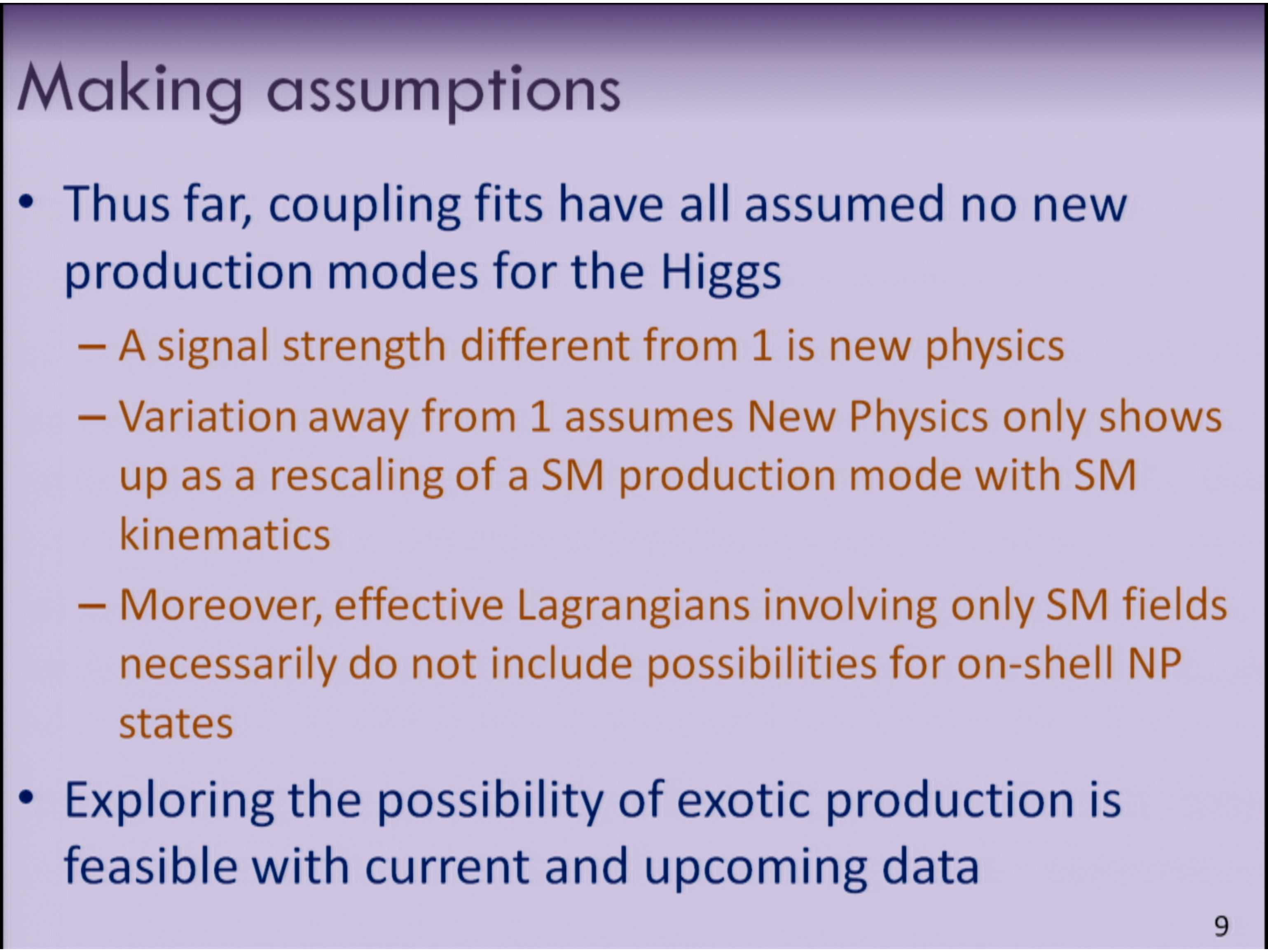


Higgs Measurements – introducing NP

- Alternatively, can consider higher dimension operators and fit for coefficients
- As an illustration: light Higgs as a Goldstone boson

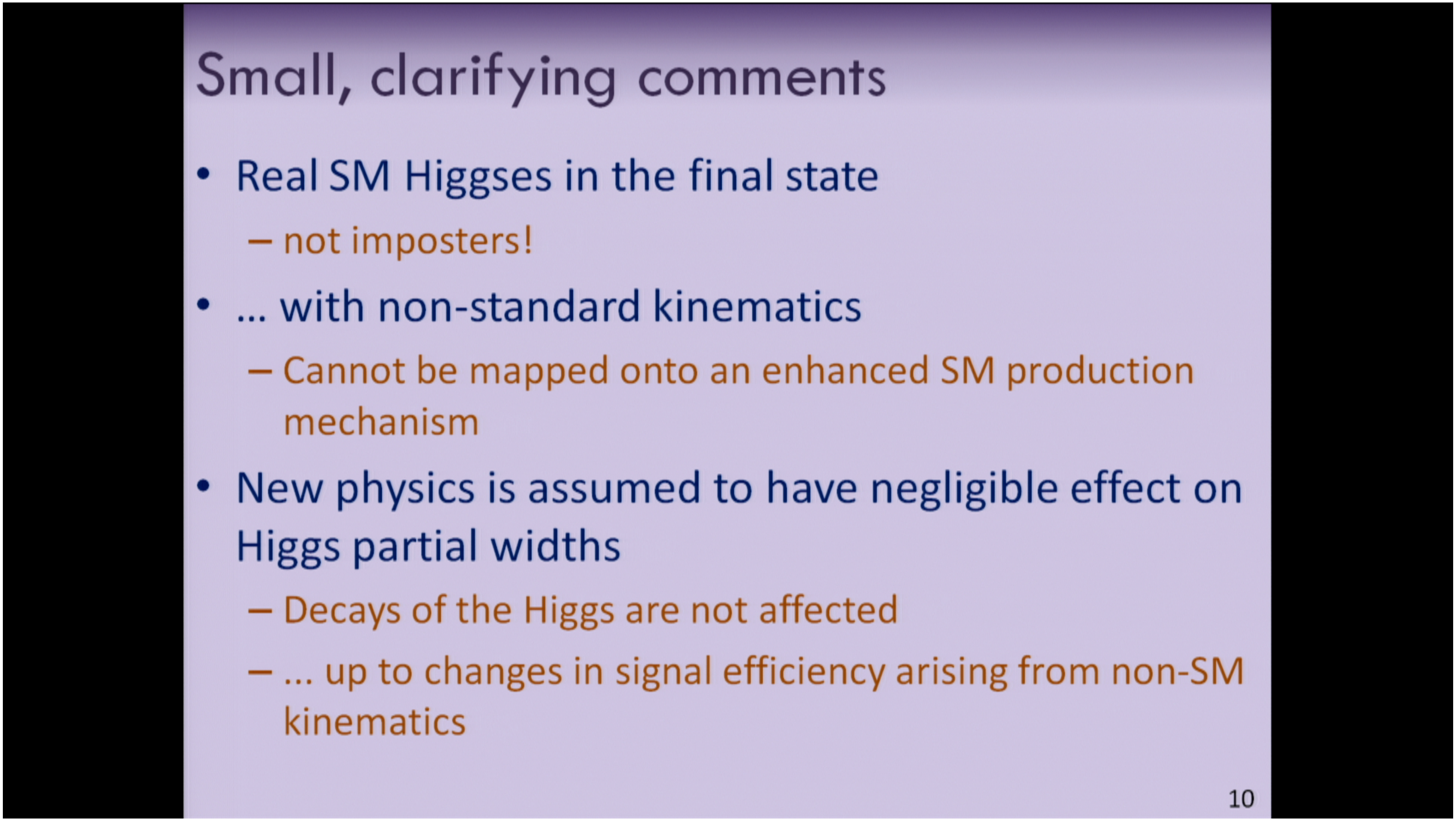
$$
\begin{aligned}
\Delta\mathcal{L}_{SILH} = {} & \frac{\bar{c}_H}{2v^2}\,\partial^\mu\left(H^\dagger H\right)\partial_\mu\left(H^\dagger H\right) + \frac{\bar{c}_T}{2v^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) - \frac{\bar{c}_6\,\lambda}{v^2}\left(H^\dagger H\right)^3 \\
& + \left(\left(\frac{\bar{c}_u}{v^2}\,y_u\,H^\dagger H\,\bar{q}_L H^c u_R + \frac{\bar{c}_d}{v^2}\,y_d\,H^\dagger H\,\bar{q}_L H d_R + \frac{\bar{c}_l}{v^2}\,y_l\,H^\dagger H\,\bar{L}_L H l_R\right) + h.c.\right) \\
& + \frac{i\bar{c}_W\,g}{2m_W^2}\left(H^\dagger \sigma^i \overleftrightarrow{D^\mu} H\right)\left(D^\nu W_{\mu\nu}\right)^i + \frac{i\bar{c}_B\,g'}{2m_W^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)\left(\partial^\nu B_{\mu\nu}\right) \\
& + \frac{i\bar{c}_{HW}\,g}{m_W^2}\left(D^\mu H\right)^\dagger \sigma^i \left(D^\nu H\right) W^i_{\mu\nu} + \frac{i\bar{c}_{HB}\,g'}{m_W^2}\left(D^\mu H\right)^\dagger\left(D^\nu H\right) B_{\mu\nu} \\
& + \frac{\bar{c}_\gamma\,g'^2}{m_W^2}\,H^\dagger H\,B_{\mu\nu}B^{\mu\nu} + \frac{\bar{c}_g\,g_S^2}{m_W^2}\,H^\dagger H\,G^a_{\mu\nu}G^{a\mu\nu}\,,
\end{aligned}
$$

Giudice, Grojean, Pomarol, Rattazzi (hep-ph/0703164)
Contino, Ghezzi, Grojean, Muhlleitner, Spira (1303.3876)
Azatov, Contino, Iura, Galloway (1308.2676) + more



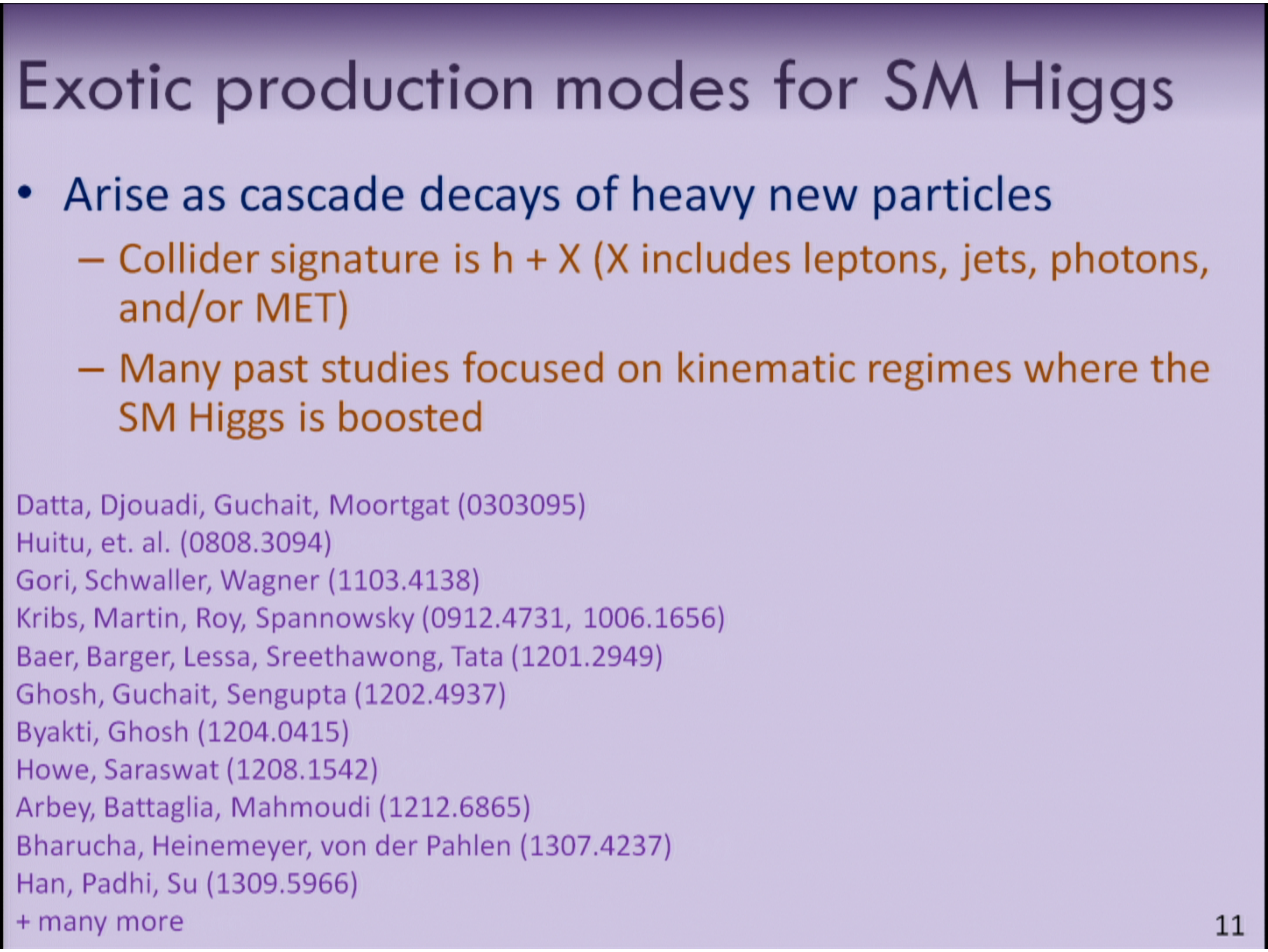
Making assumptions

- Thus far, coupling fits have all assumed no new production modes for the Higgs
  - A signal strength different from 1 is new physics
  - Variation away from 1 assumes New Physics only shows up as a rescaling of a SM production mode with SM kinematics
  - Moreover, effective Lagrangians involving only SM fields necessarily do not include possibilities for on-shell NP states
- Exploring the possibility of exotic production is feasible with current and upcoming data



Small, clarifying comments

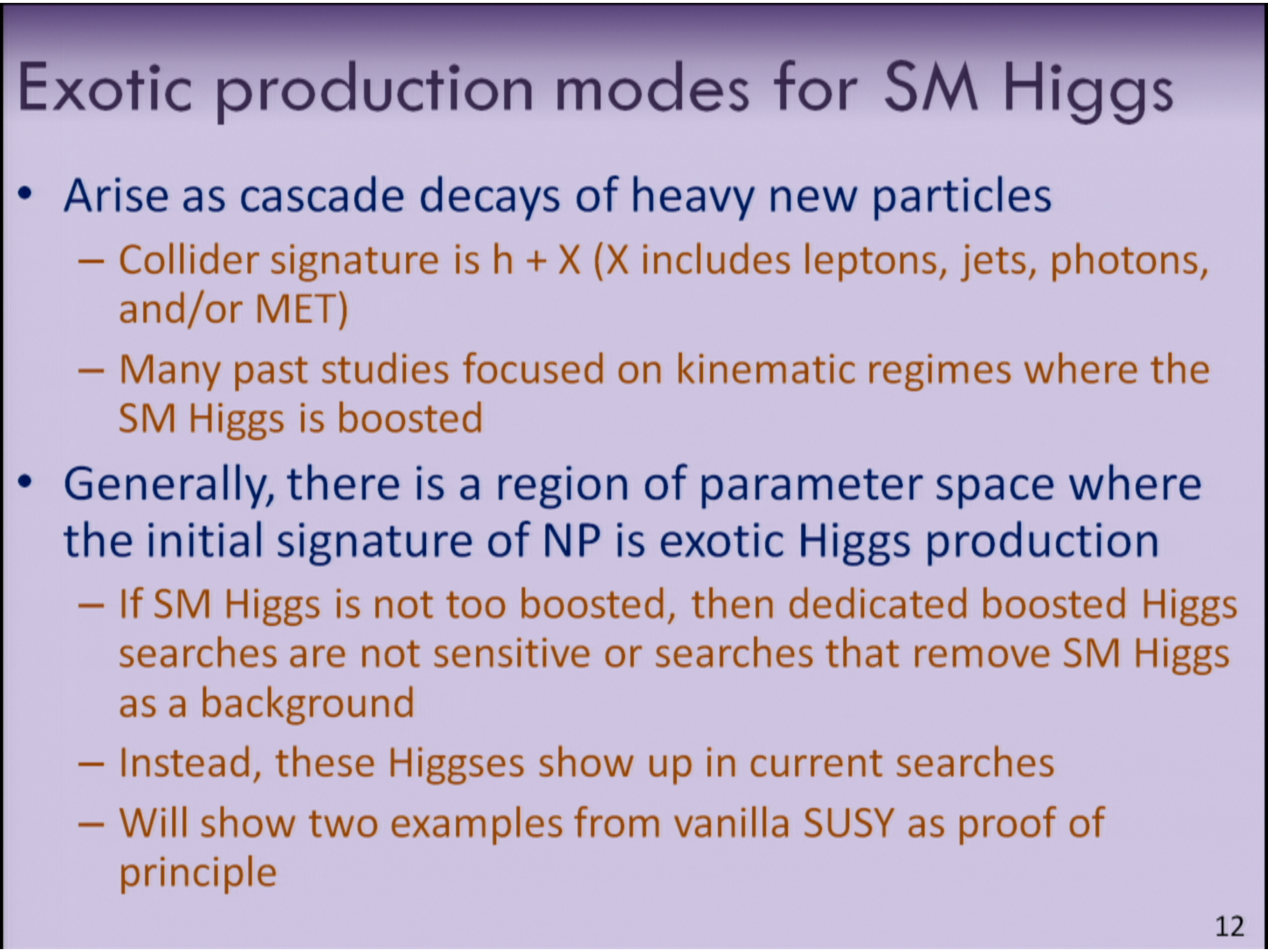
- Real SM Higgses in the final state
  - not imposters!
- … with non-standard kinematics
  - Cannot be mapped onto an enhanced SM production mechanism
- New physics is assumed to have negligible effect on Higgs partial widths
  - Decays of the Higgs are not affected
  - … up to changes in signal efficiency arising from non-SM kinematics



Exotic production modes for SM Higgs

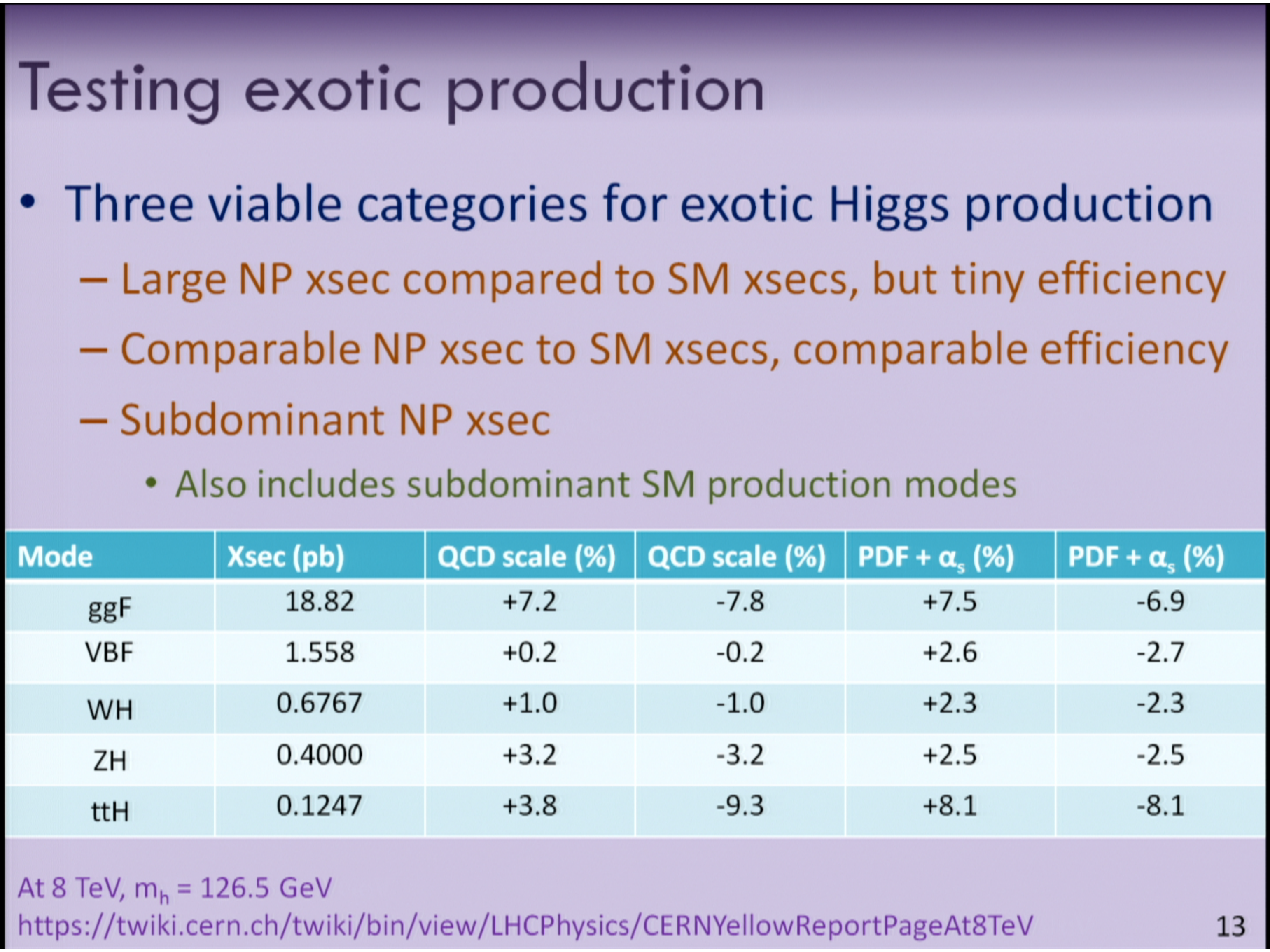
- Arise as cascade decays of heavy new particles
  - Collider signature is h + X (X includes leptons, jets, photons, and/or MET)
  - Many past studies focused on kinematic regimes where the SM Higgs is boosted

Datta, Djouadi, Guchait, Moortgat (0303095)
Huitu, et. al. (0808.3094)
Gori, Schwaller, Wagner (1103.4138)
Kribs, Martin, Roy, Spannowsky (0912.4731, 1006.1656)
Baer, Barger, Lessa, Sreethawong, Tata (1201.2949)
Ghosh, Guchait, Sengupta (1202.4937)
Byakti, Ghosh (1204.0415)
Howe, Saraswat (1208.1542)
Arbey, Battaglia, Mahmoudi (1212.6865)
Bharucha, Heinemeyer, von der Pahlen (1307.4237)
Han, Padhi, Su (1309.5966)
+ many more



Exotic production modes for SM Higgs

- Arise as cascade decays of heavy new particles
  - Collider signature is h + X (X includes leptons, jets, photons, and/or MET)
  - Many past studies focused on kinematic regimes where the SM Higgs is boosted
- Generally, there is a region of parameter space where the initial signature of NP is exotic Higgs production
  - If SM Higgs is not too boosted, then dedicated boosted Higgs searches are not sensitive or searches that remove SM Higgs as a background
  - Instead, these Higgses show up in current searches
  - Will show two examples from vanilla SUSY as proof of principle

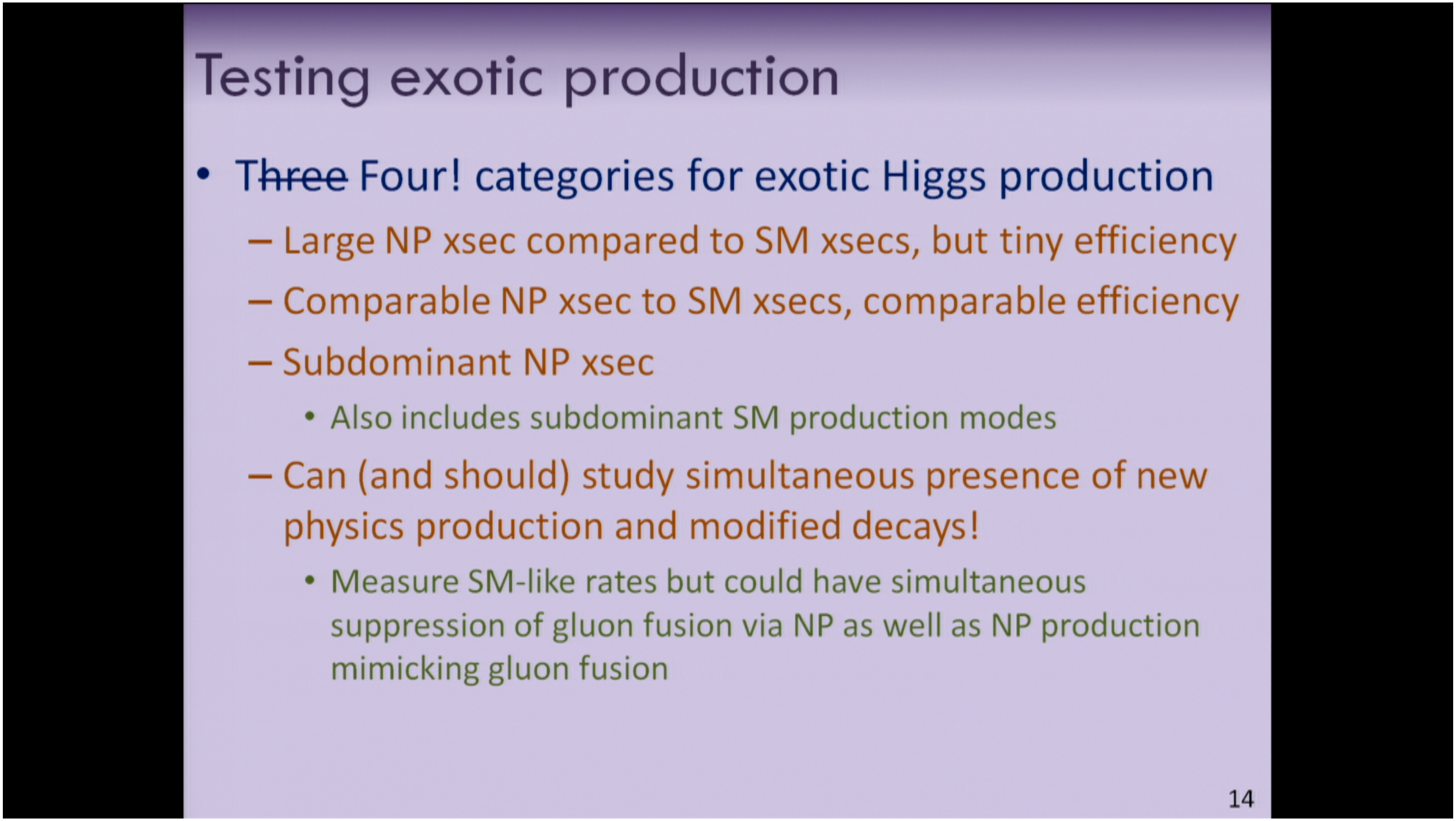


Testing exotic production

- Three viable categories for exotic Higgs production
  - Large NP xsec compared to SM xsecs, but tiny efficiency
  - Comparable NP xsec to SM xsecs, comparable efficiency
  - Subdominant NP xsec
    - Also includes subdominant SM production modes

Mode	Xsec (pb)	QCD scale (%)	QCD scale (%)	PDF + α_s (%)	PDF + α_s (%)
ggF	18.82	+7.2	-7.8	+7.5	-6.9
VBF	1.558	+0.2	-0.2	+2.6	-2.7
WH	0.6767	+1.0	-1.0	+2.3	-2.3
ZH	0.4000	+3.2	-3.2	+2.5	-2.5
ttH	0.1247	+3.8	-9.3	+8.1	-8.1

At 8 TeV, m_h = 126.5 GeV
https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CERNYellowReportPageAt8TeV

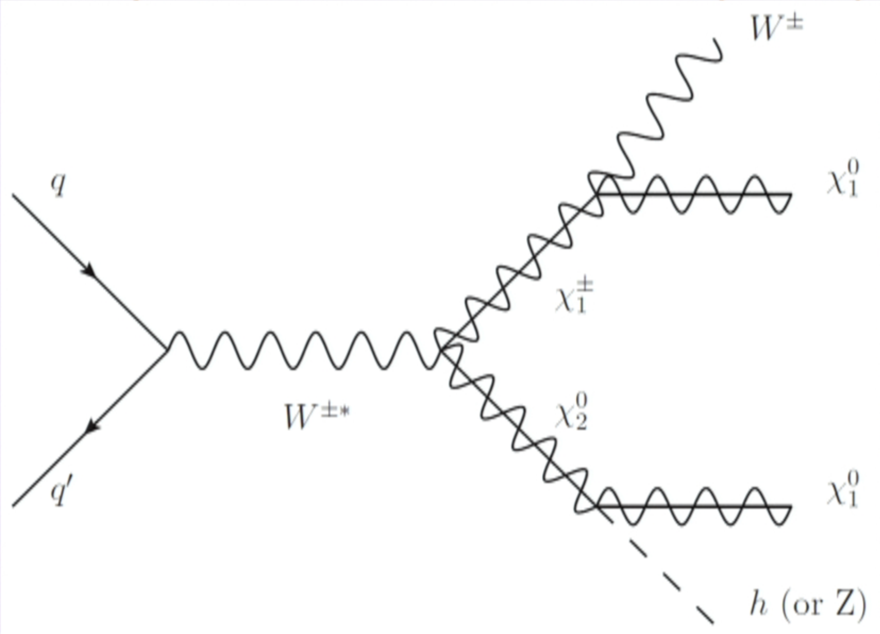


Testing exotic production

- ~~Three~~ Four! categories for exotic Higgs production
  - Large NP xsec compared to SM xsecs, but tiny efficiency
  - Comparable NP xsec to SM xsecs, comparable efficiency
  - Subdominant NP xsec
    - Also includes subdominant SM production modes
  - Can (and should) study simultaneous presence of new physics production and modified decays!
    - Measure SM-like rates but could have simultaneous suppression of gluon fusion via NP as well as NP production mimicking gluon fusion

Testing exotic production

- Consider the concrete case of chargino-neutralino production at LHC
  - Gives final states of $W^{\pm}Z$ + MET or $W^{\pm}h$ + MET (kinematically forbid intermediate sleptons)



Testing exotic production

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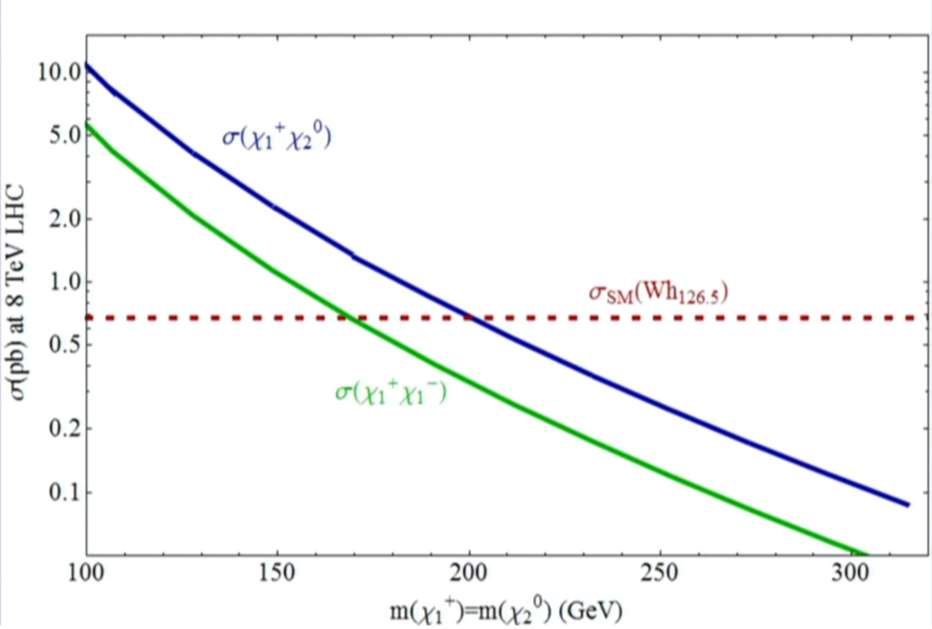
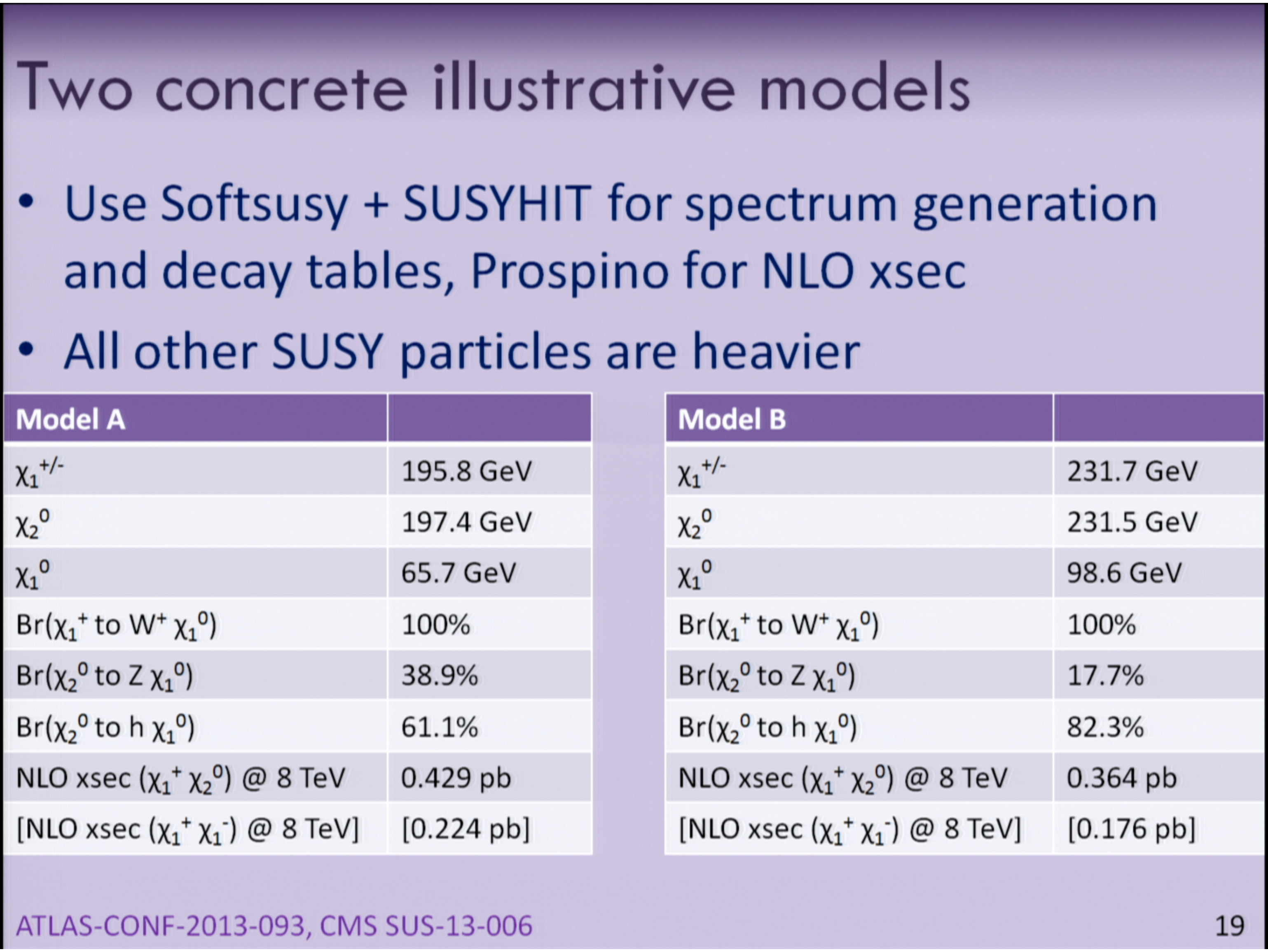
Aside:

At 8 TeV, CMS measures $\sigma(W^+W^-)$ to be 69.9 ± 2.8 (stat.) ± 5.6 (syst.) ± 3.1 (lum.) pb [1301.4698]

MCFM (NLO SM prediction) is $57.3^{+2.3}_{-1.6}$ pb





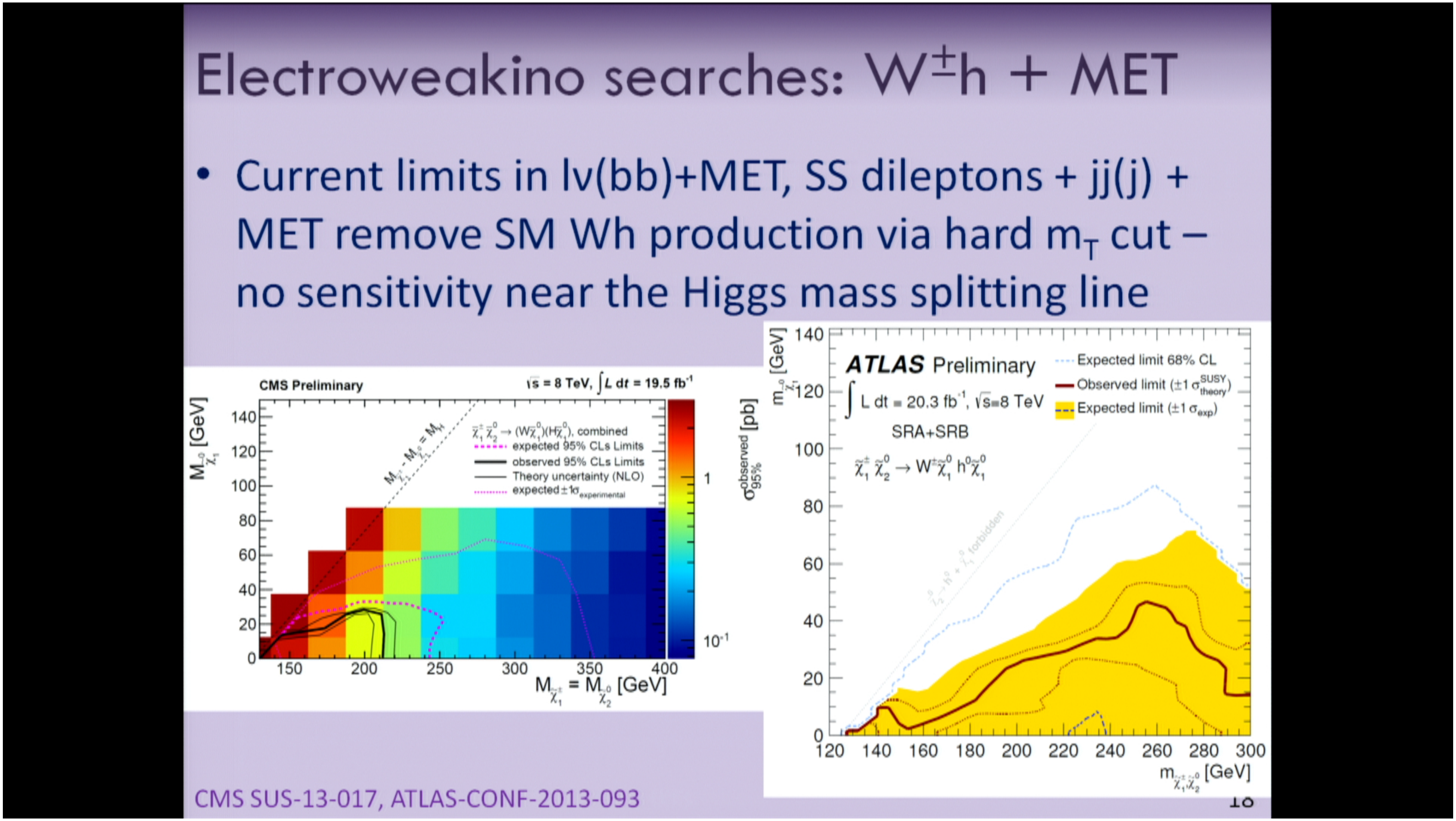
Two concrete illustrative models

- Use Softsusy + SUSYHIT for spectrum generation and decay tables, Prospino for NLO xsec
- All other SUSY particles are heavier

Model A	
$\chi_1^{+/-}$	195.8 GeV
χ_2^0	197.4 GeV
χ_1^0	65.7 GeV
Br(χ_1^+ to $W^+ \chi_1^0$)	100%
Br(χ_2^0 to Z χ_1^0)	38.9%
Br(χ_2^0 to h χ_1^0)	61.1%
NLO xsec ($\chi_1^+ \chi_2^0$) @ 8 TeV	0.429 pb
[NLO xsec ($\chi_1^+ \chi_1^-$) @ 8 TeV]	[0.224 pb]

Model B	
$\chi_1^{+/-}$	231.7 GeV
χ_2^0	231.5 GeV
χ_1^0	98.6 GeV
Br(χ_1^+ to $W^+ \chi_1^0$)	100%
Br(χ_2^0 to Z χ_1^0)	17.7%
Br(χ_2^0 to h χ_1^0)	82.3%
NLO xsec ($\chi_1^+ \chi_2^0$) @ 8 TeV	0.364 pb
[NLO xsec ($\chi_1^+ \chi_1^-$) @ 8 TeV]	[0.176 pb]

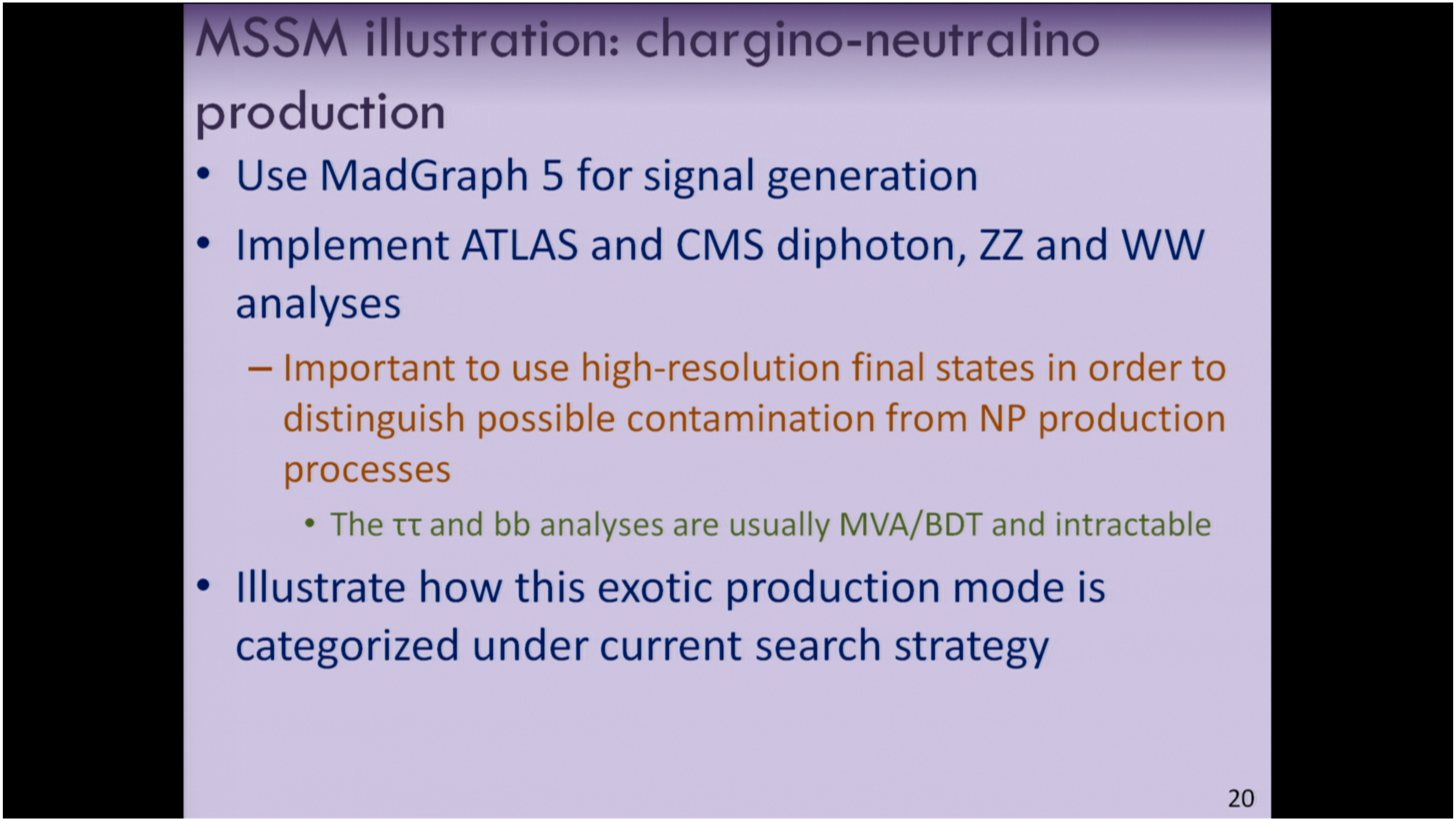
ATLAS-CONF-2013-093, CMS SUS-13-006



Electroweakino searches: $W^{\pm}h$ + MET

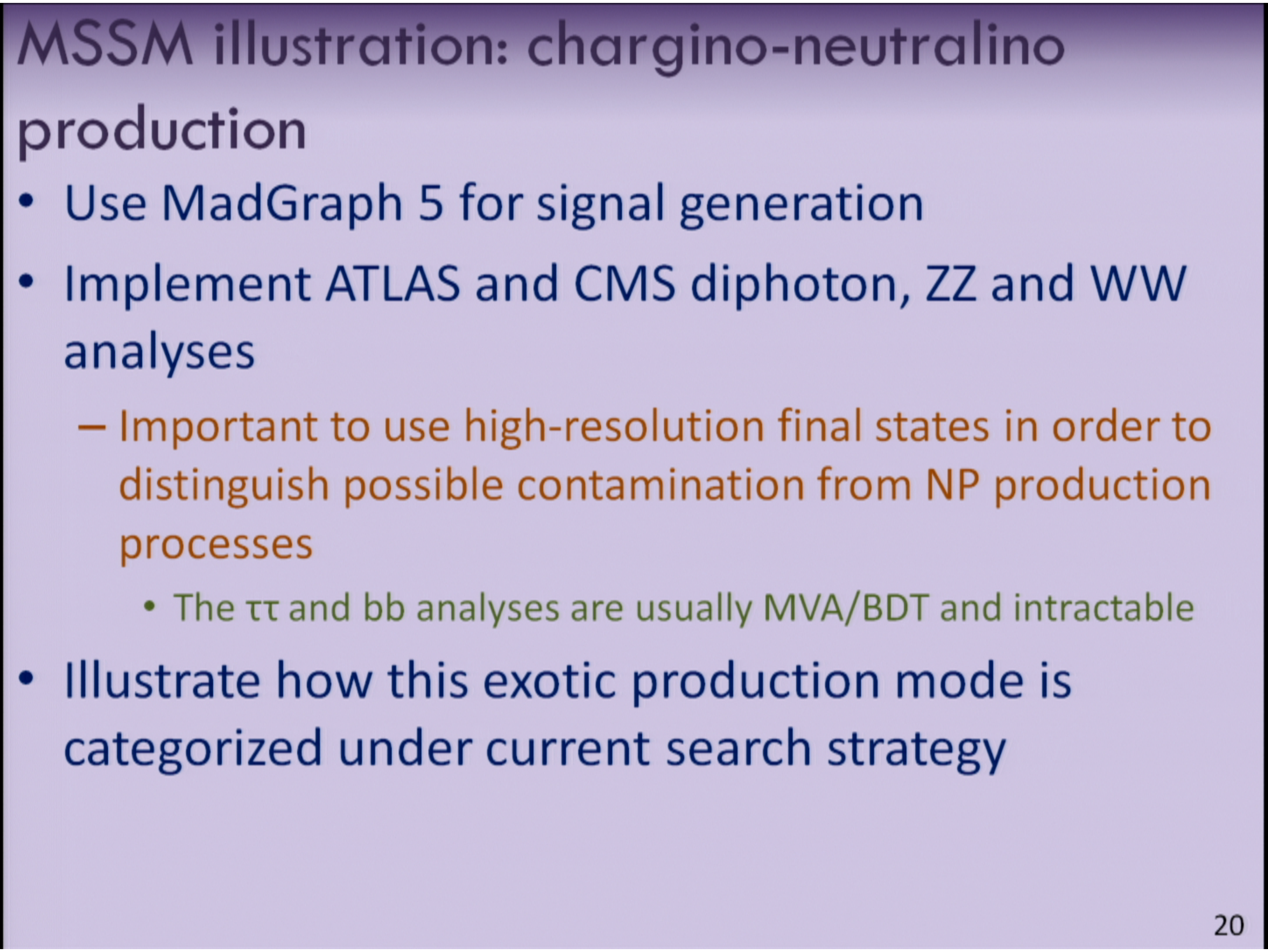
- Current limits in lν(bb)+MET, SS dileptons + jj(j) + MET remove SM Wh production via hard m_T cut – no sensitivity near the Higgs mass splitting line

CMS SUS-13-017, ATLAS-CONF-2013-093



MSSM illustration: chargino-neutralino production

- Use MadGraph 5 for signal generation
- Implement ATLAS and CMS diphoton, ZZ and WW analyses
  - Important to use high-resolution final states in order to distinguish possible contamination from NP production processes
    - The ττ and bb analyses are usually MVA/BDT and intractable
- Illustrate how this exotic production mode is categorized under current search strategy



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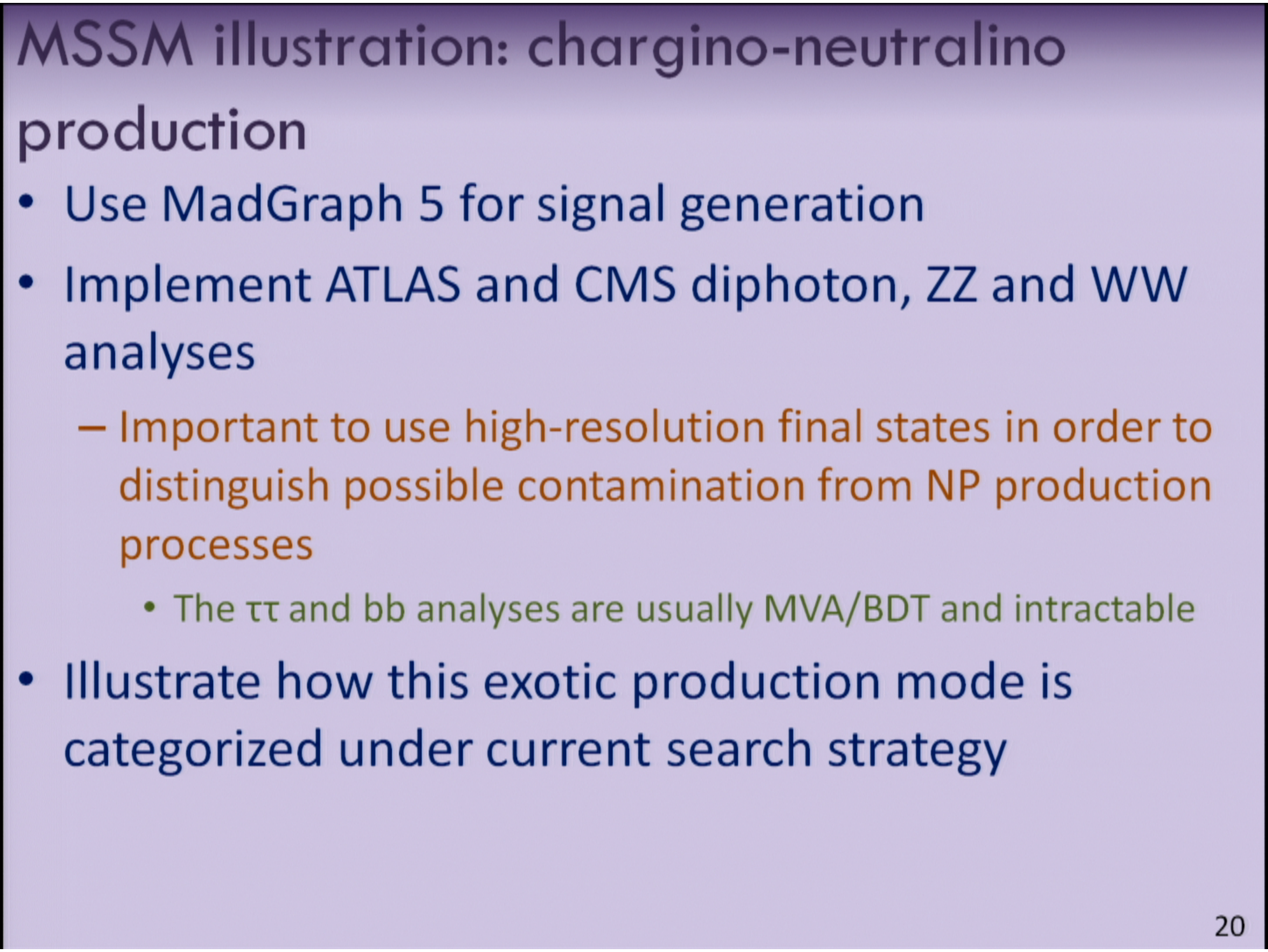

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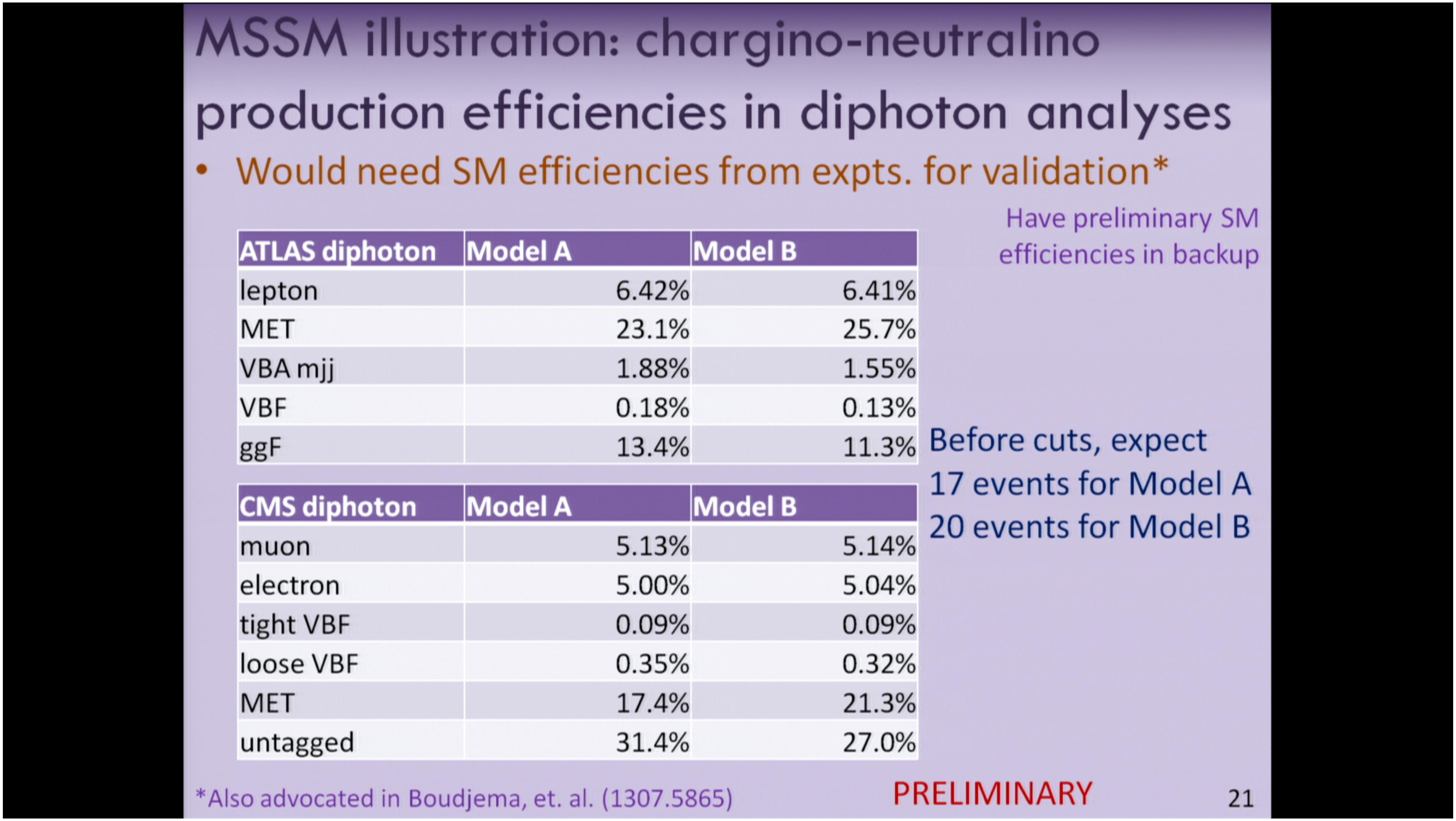


MSSM illustration: chargino-neutralino production efficiencies in diphoton analyses

- Would need SM efficiencies from expts. for validation*

Have preliminary SM efficiencies in backup

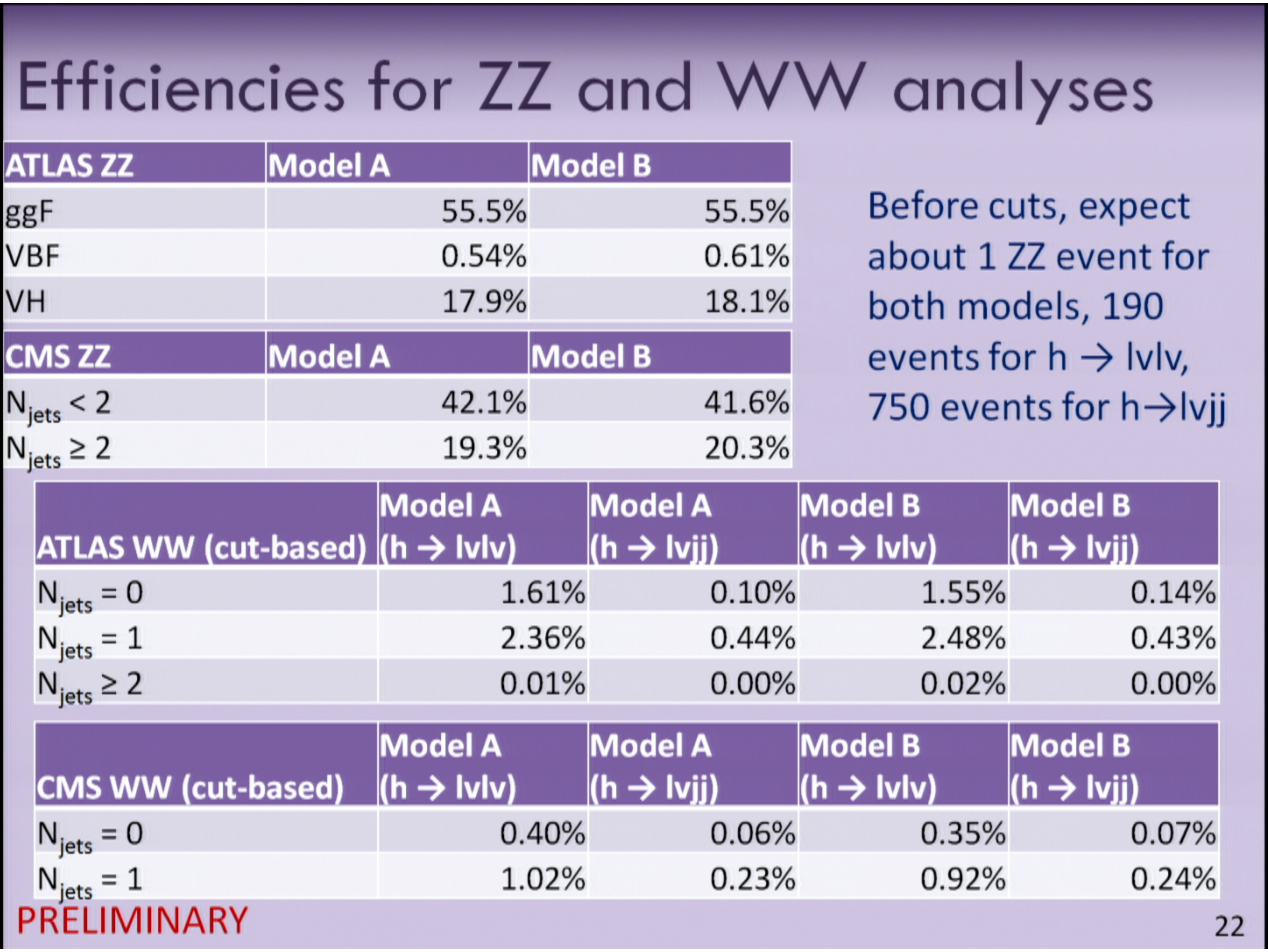
ATLAS diphoton	Model A	Model B
lepton	6.42%	6.41%
MET	23.1%	25.7%
VBA mjj	1.88%	1.55%
VBF	0.18%	0.13%
ggF	13.4%	11.3%

CMS diphoton	Model A	Model B
muon	5.13%	5.14%
electron	5.00%	5.04%
tight VBF	0.09%	0.09%
loose VBF	0.35%	0.32%
MET	17.4%	21.3%
untagged	31.4%	27.0%

Before cuts, expect
17 events for Model A
20 events for Model B

*Also advocated in Boudjema, et. al. (1307.5865)

PRELIMINARY



Efficiencies for ZZ and WW analyses

ATLAS ZZ	Model A	Model B
ggF	55.5%	55.5%
VBF	0.54%	0.61%
VH	17.9%	18.1%

CMS ZZ	Model A	Model B
$N_{jets} < 2$	42.1%	41.6%
$N_{jets} \geq 2$	19.3%	20.3%

Before cuts, expect about 1 ZZ event for both models, 190 events for h → lvlv, 750 events for h→lvjj

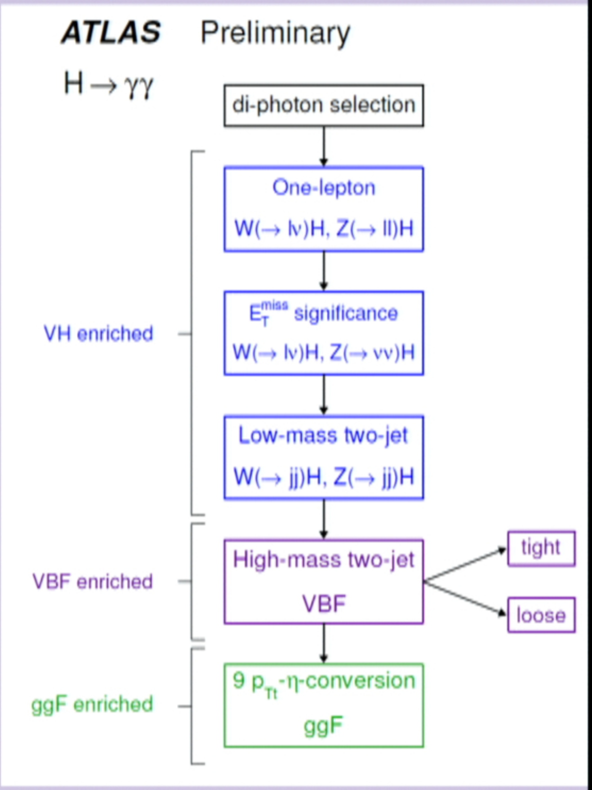
ATLAS WW (cut-based)	Model A (h → lvlv)	Model A (h → lvjj)	Model B (h → lvlv)	Model B (h → lvjj)
$N_{jets} = 0$	1.61%	0.10%	1.55%	0.14%
$N_{jets} = 1$	2.36%	0.44%	2.48%	0.43%
$N_{jets} \geq 2$	0.01%	0.00%	0.02%	0.00%

CMS WW (cut-based)	Model A (h → lvlv)	Model A (h → lvjj)	Model B (h → lvlv)	Model B (h → lvjj)
$N_{jets} = 0$	0.40%	0.06%	0.35%	0.07%
$N_{jets} = 1$	1.02%	0.23%	0.92%	0.24%

PRELIMINARY

Understanding diphoton efficiencies

- The diphoton analyses uses associated objects and their kinematics to categorize the events
  - Important to note that gluon fusion is the catch-all category
  - Each final category has contamination from other SM production modes
- Since exotic production will have different categorization efficiencies, cannot use a rescaling of a SM production mode to capture the NP effects



ATLAS Preliminary

$H \rightarrow \gamma\gamma$

di-photon selection

VH enriched

One-lepton
$W(\rightarrow l\nu)H$, $Z(\rightarrow ll)H$

E_T^{miss} significance
$W(\rightarrow l\nu)H$, $Z(\rightarrow \nu\nu)H$

Low-mass two-jet
$W(\rightarrow jj)H$, $Z(\rightarrow jj)H$

VBF enriched

High-mass two-jet
VBF

tight

loose

ggF enriched

9 p_{Tt}-η-conversion
ggF

ATLAS-CONF-2013-012

Expanding to more models

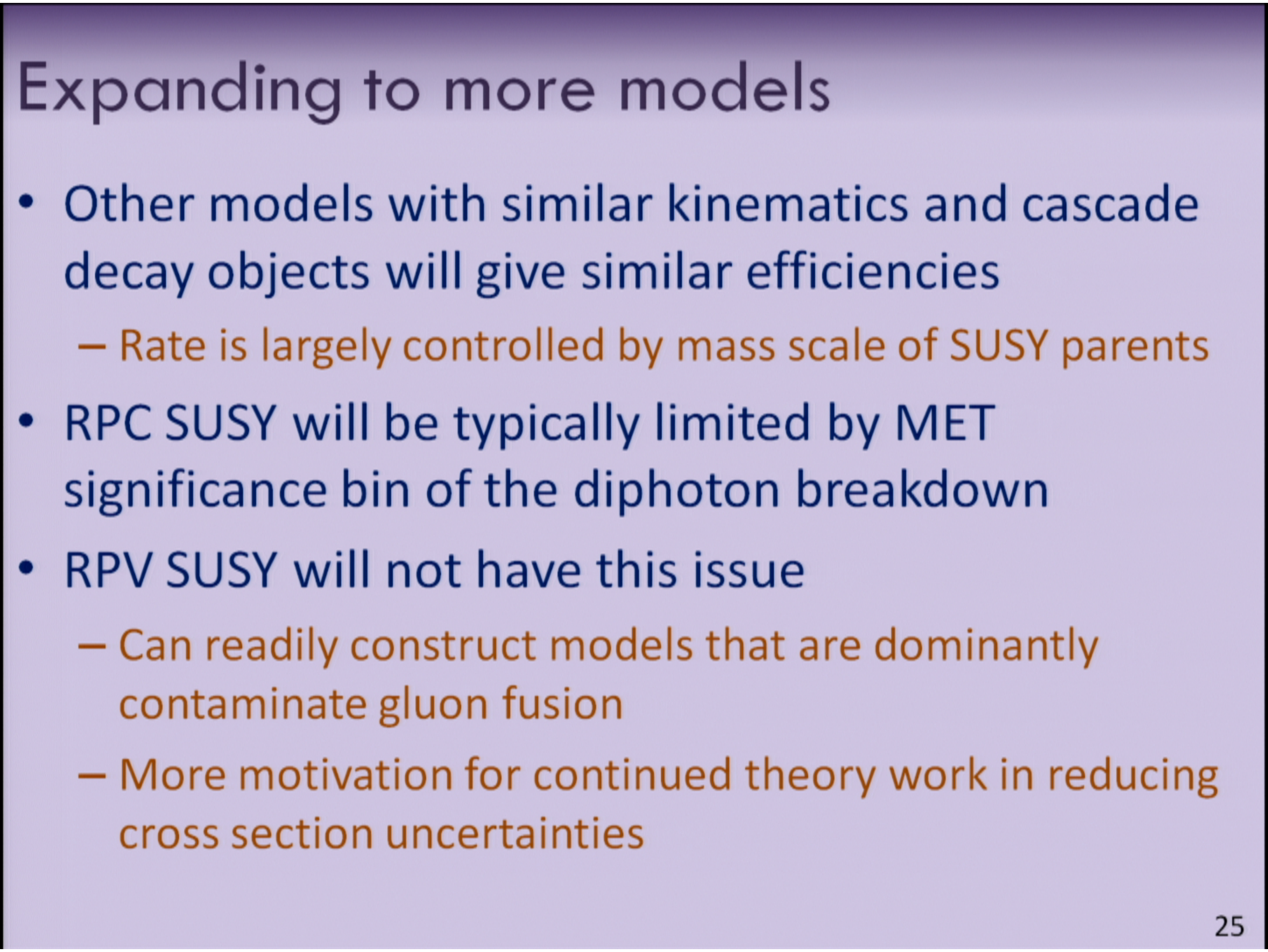
- Other models with similar kinematics and cascade decay objects will give similar efficiencies
  - Rate is largely controlled by mass scale of SUSY parents
- RPC SUSY will be typically limited by MET significance bin of the diphoton breakdown

Diphoton 8 TeV counts: expected background and SM signal contributions

Can constrain chargino-neutralino production along Higgs mass splitting line

ATLAS (1307.1427)

Category	N_D	N_B	N_S	ggF	VBF	WH	ZH	$t\bar{t}H$
Untagged	14248	13582	350	320	19	7.0	4.2	1.0
Loose high-mass two-jet	41	28	5.0	2.3	2.7	< 0.1	< 0.1	< 0.1
Tight high-mass two-jet	23	13	7.7	1.8	5.9	< 0.1	< 0.1	< 0.1
Low-mass two-jet	19	21	3.1	1.5	< 0.1	0.92	0.54	< 0.1
E_T^{miss} significance	8	4	1.2	< 0.1	< 0.1	0.43	0.57	0.14
Lepton	20	12	2.7	< 0.1	< 0.1	1.7	0.41	0.50
All categories (inclusive)	13931	13205	370	330	27	10	5.8	1.7

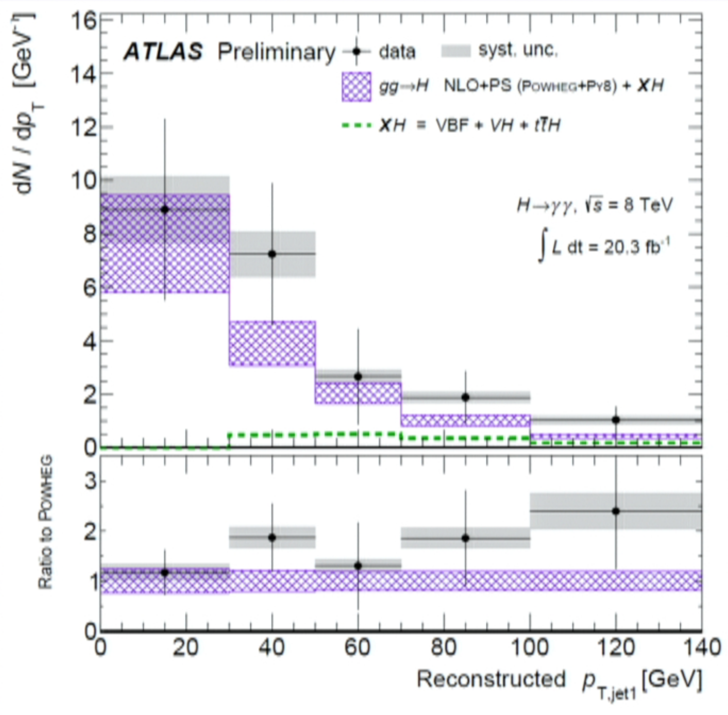


Expanding to more models

- Other models with similar kinematics and cascade decay objects will give similar efficiencies
  - Rate is largely controlled by mass scale of SUSY parents
- RPC SUSY will be typically limited by MET significance bin of the diphoton breakdown
- RPV SUSY will not have this issue
  - Can readily construct models that are dominantly contaminate gluon fusion
  - More motivation for continued theory work in reducing cross section uncertainties

Testing for exotic production

- For h+X from new physics, should test counts and kinematics X (= leptons, jets, photons, MET)

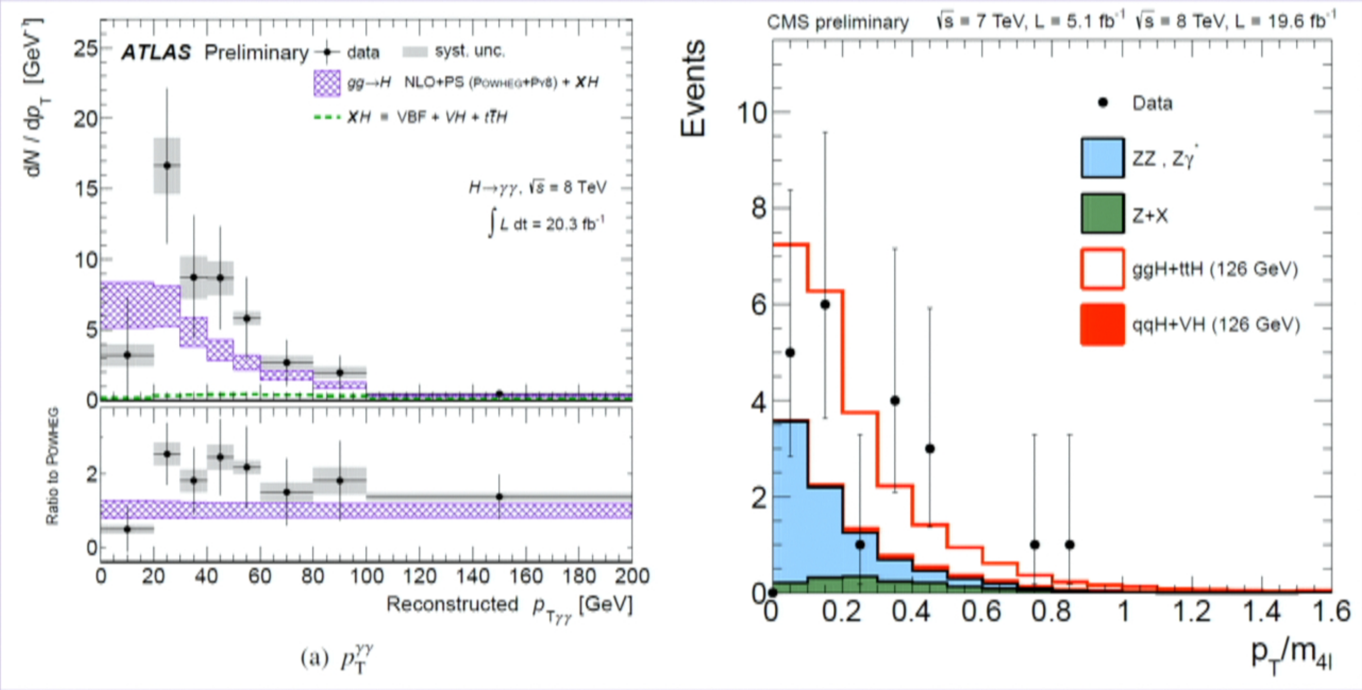


(d) $p_T^{j_1}$

ATLAS CONF-2013-072

Testing for exotic production

- Also should test the p_T of the Higgs candidates
  - Need continued theory work on differential distributions

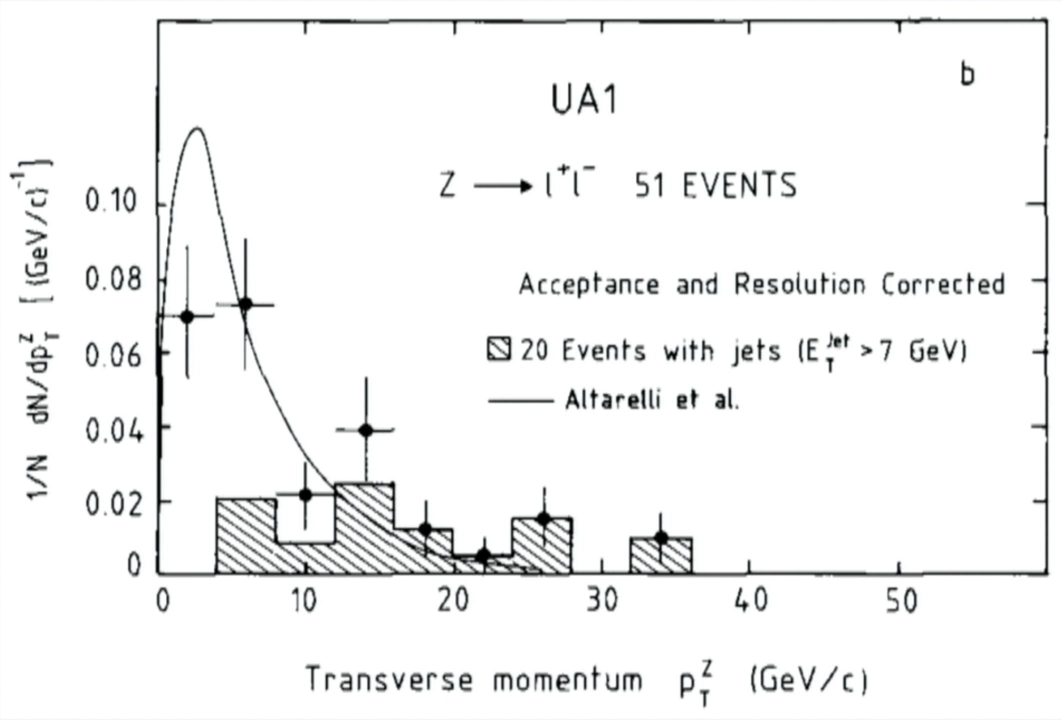


(a) $p_T^{\gamma\gamma}$

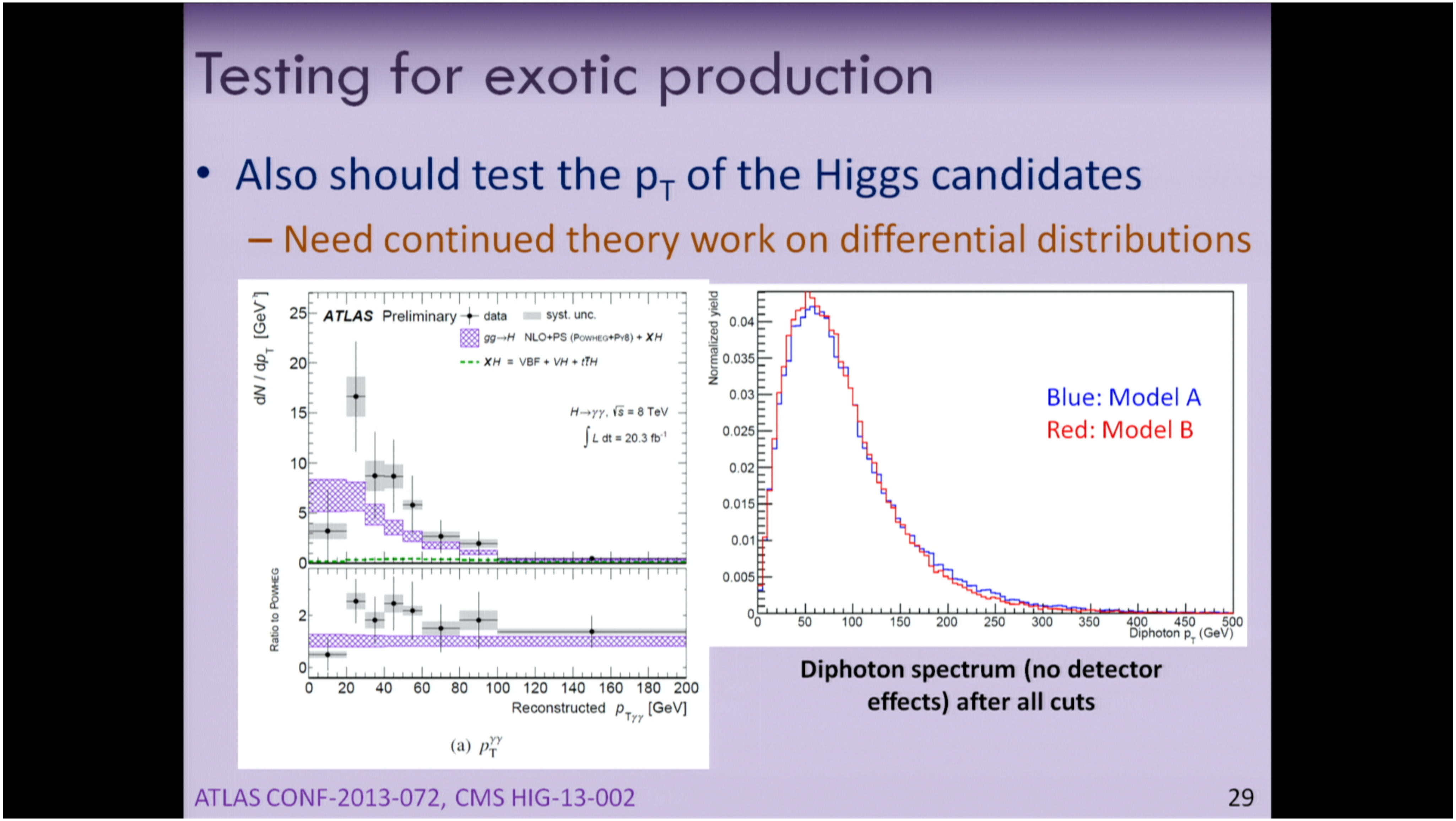
ATLAS CONF-2013-072, CMS HIG-13-002

Testing for exotic production

- Also should test the p_T of the Higgs candidates
  - Statistics limited, but we're at the beginning stage



UA1, Z.Phys. C44 (1989) 15-61 (h/t Mangano)



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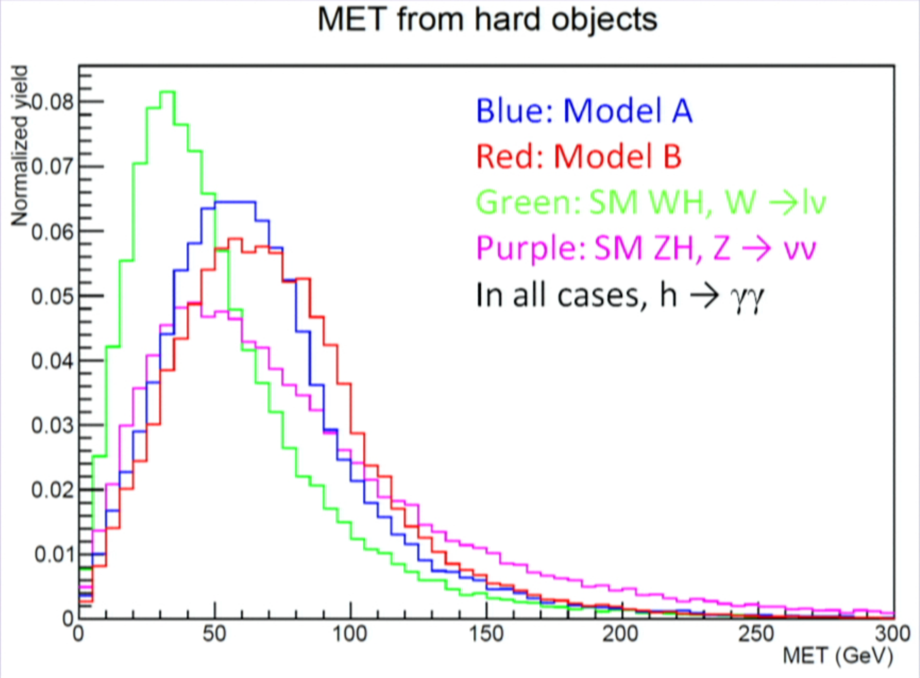
(a) $p_T^{\gamma\gamma}$

Diphoton spectrum (no detector effects) after all cuts

ATLAS CONF-2013-072, CMS HIG-13-002

Testing for exotic production

- Also should look at MET distributions
- Disentangling these shapes requires high-resolution final states (*e.g.* 4l or γγ)



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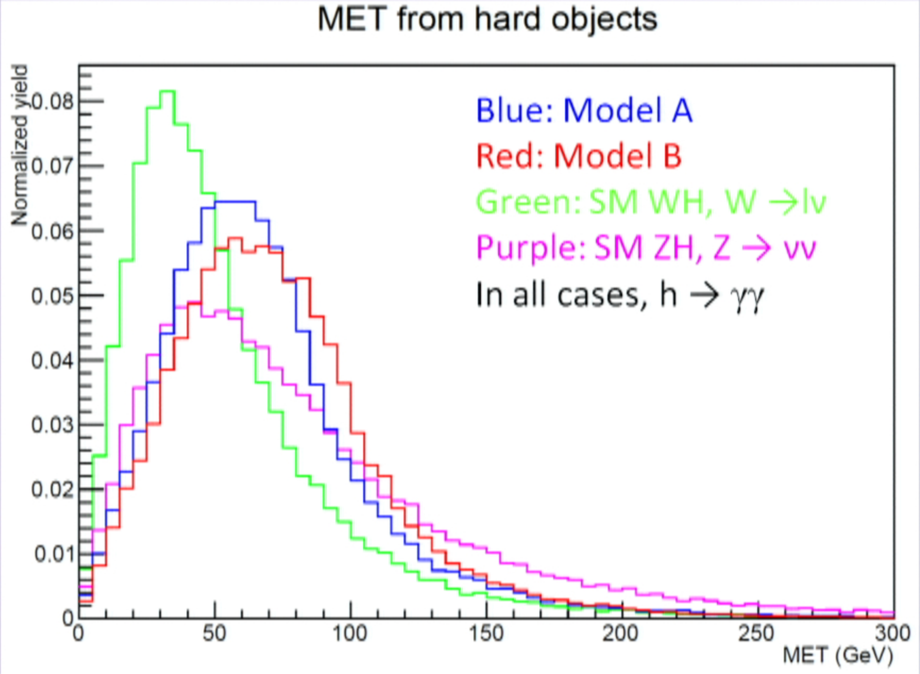
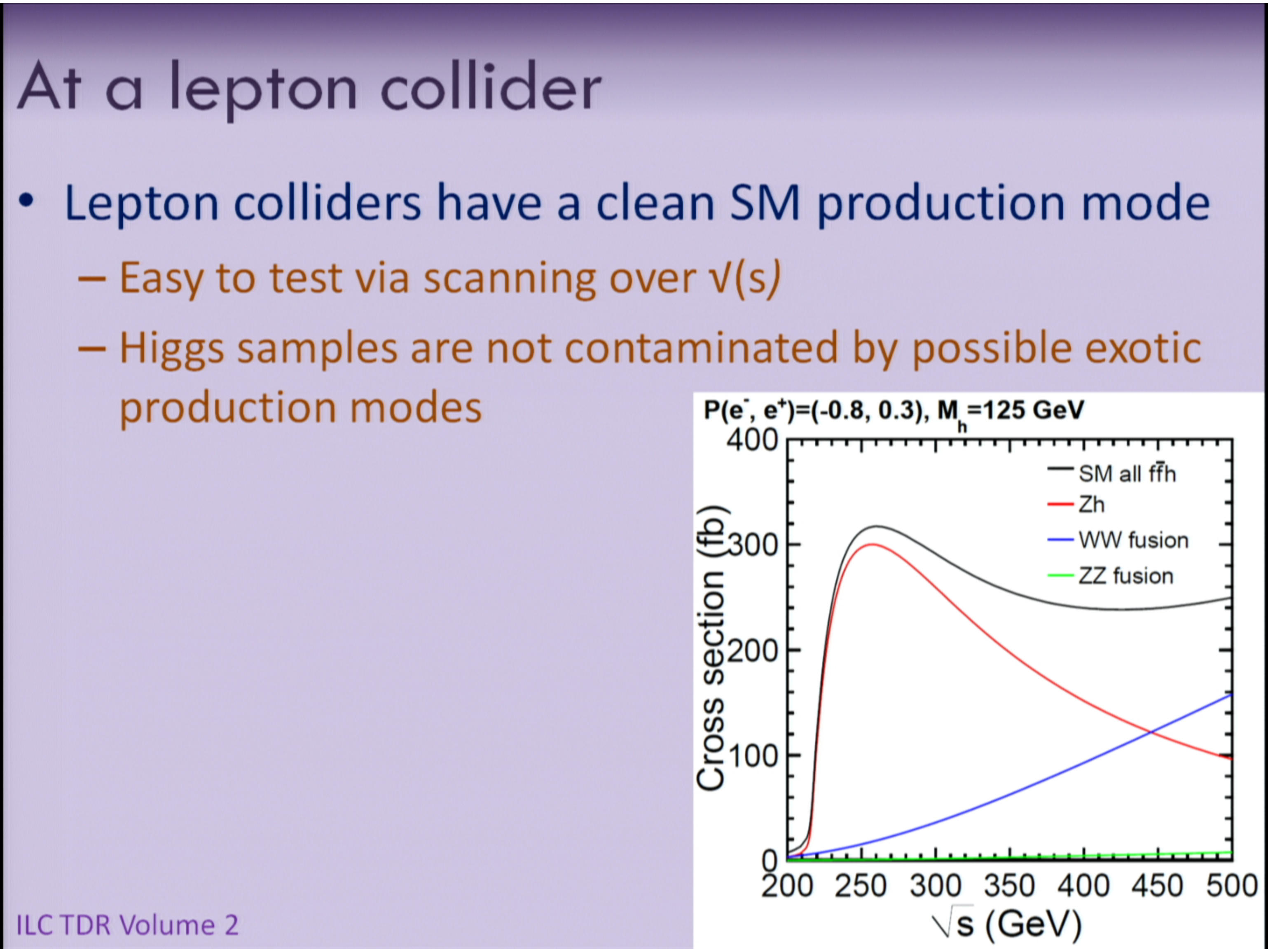




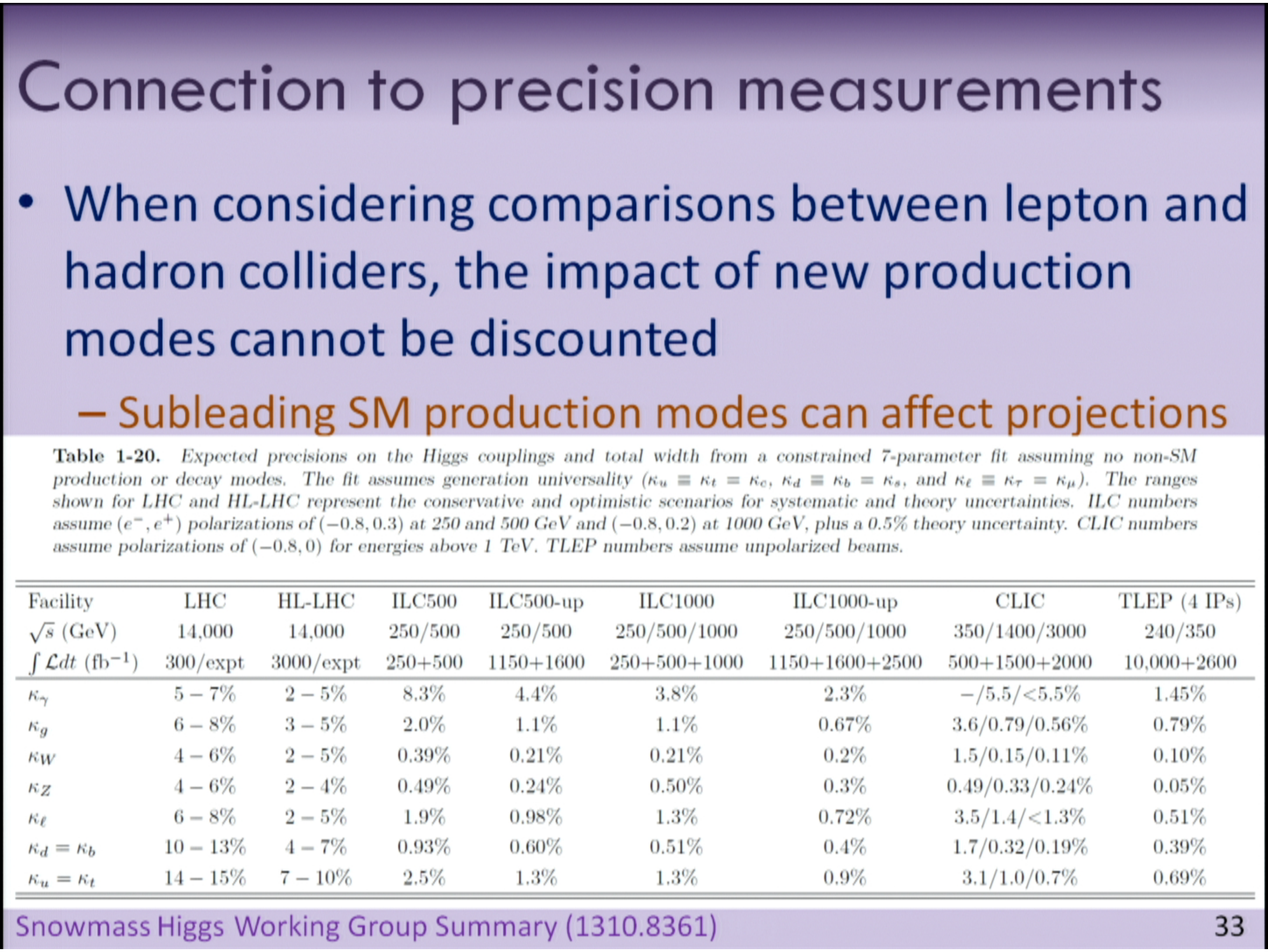
At a lepton collider

- Lepton colliders have a clean SM production mode
  - Easy to test via scanning over √(s)
  - Higgs samples are not contaminated by possible exotic production modes

ILC TDR Volume 2

At a lepton collider

- Lepton colliders have a clean SM production mode
  - Easy to test via scanning over √(s)
  - Higgs samples are not contaminated by possible exotic production modes
- The hadron and lepton Higgs datasets are truly orthogonal and complementary
  - Discrepancies between central values of extracted couplings can be resolved by exotic Higgs production



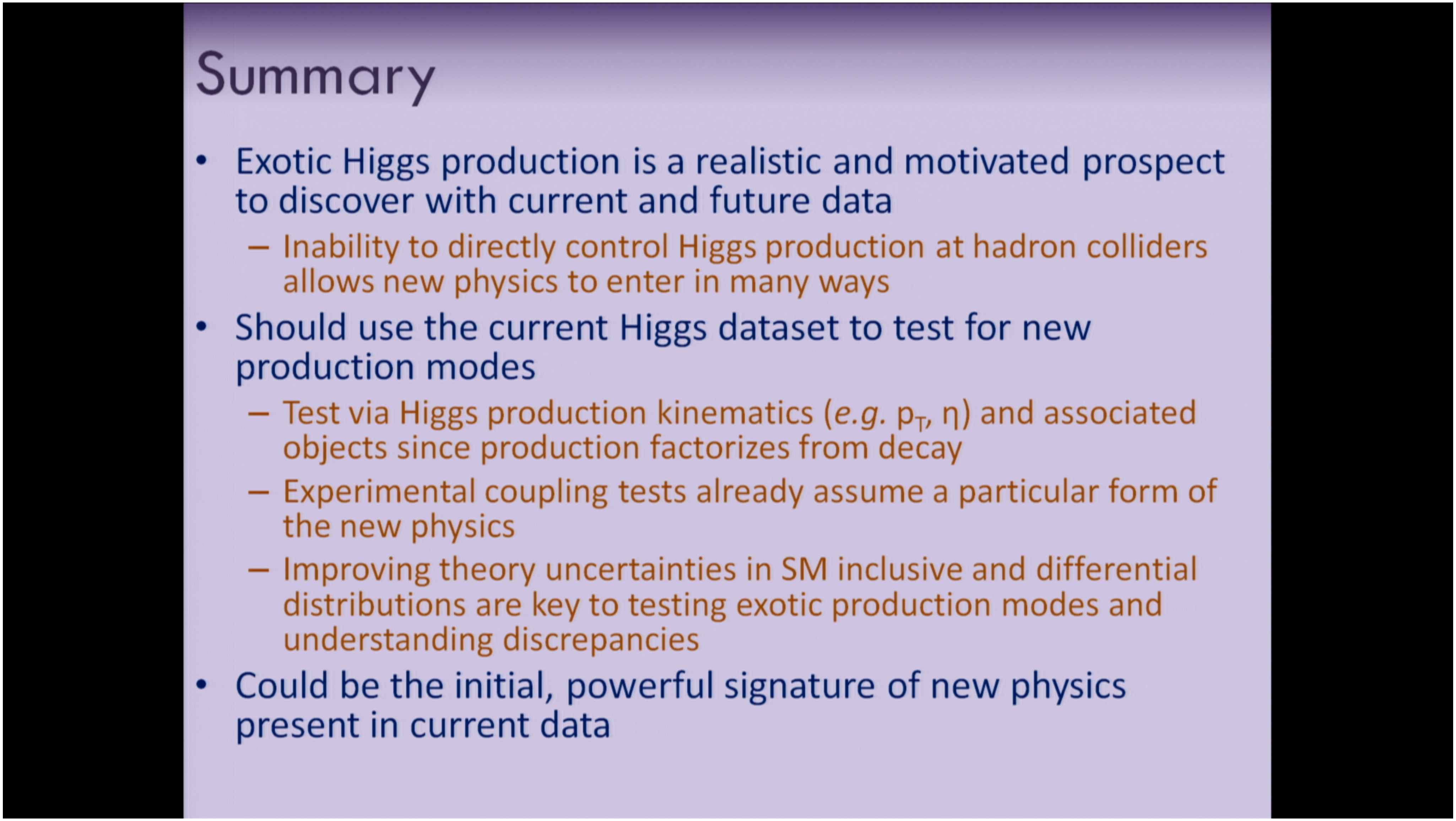
Connection to precision measurements

- When considering comparisons between lepton and hadron colliders, the impact of new production modes cannot be discounted
  - – Subleading SM production modes can affect projections

Table 1-20. *Expected precisions on the Higgs couplings and total width from a constrained 7-parameter fit assuming no non-SM production or decay modes. The fit assumes generation universality ($\kappa_u \equiv \kappa_t = \kappa_c$, $\kappa_d \equiv \kappa_b = \kappa_s$, and $\kappa_\ell \equiv \kappa_\tau = \kappa_\mu$). The ranges shown for LHC and HL-LHC represent the conservative and optimistic scenarios for systematic and theory uncertainties. ILC numbers assume (e^-, e^+) polarizations of $(-0.8, 0.3)$ at 250 and 500 GeV and $(-0.8, 0.2)$ at 1000 GeV, plus a 0.5% theory uncertainty. CLIC numbers assume polarizations of $(-0.8, 0)$ for energies above 1 TeV. TLEP numbers assume unpolarized beams.*

Facility	LHC	HL-LHC	ILC500	ILC500-up	ILC1000	ILC1000-up	CLIC	TLEP (4 IPs)
$\sqrt{s}$ (GeV)	14,000	14,000	250/500	250/500	250/500/1000	250/500/1000	350/1400/3000	240/350
$\int \mathcal{L}dt$ (fb^{-1})	300/expt	3000/expt	250+500	1150+1600	250+500+1000	1150+1600+2500	500+1500+2000	10,000+2600
κ_γ	5 – 7%	2 – 5%	8.3%	4.4%	3.8%	2.3%	–/5.5/<5.5%	1.45%
κ_g	6 – 8%	3 – 5%	2.0%	1.1%	1.1%	0.67%	3.6/0.79/0.56%	0.79%
κ_W	4 – 6%	2 – 5%	0.39%	0.21%	0.21%	0.2%	1.5/0.15/0.11%	0.10%
κ_Z	4 – 6%	2 – 4%	0.49%	0.24%	0.50%	0.3%	0.49/0.33/0.24%	0.05%
κ_ℓ	6 – 8%	2 – 5%	1.9%	0.98%	1.3%	0.72%	3.5/1.4/<1.3%	0.51%
$\kappa_d = \kappa_b$	10 – 13%	4 – 7%	0.93%	0.60%	0.51%	0.4%	1.7/0.32/0.19%	0.39%
$\kappa_u = \kappa_t$	14 – 15%	7 – 10%	2.5%	1.3%	1.3%	0.9%	3.1/1.0/0.7%	0.69%

Snowmass Higgs Working Group Summary (1310.8361)



Summary

- Exotic Higgs production is a realistic and motivated prospect to discover with current and future data
  - Inability to directly control Higgs production at hadron colliders allows new physics to enter in many ways
- Should use the current Higgs dataset to test for new production modes
  - Test via Higgs production kinematics (*e.g.* p_T, η) and associated objects since production factorizes from decay
  - Experimental coupling tests already assume a particular form of the new physics
  - Improving theory uncertainties in SM inclusive and differential distributions are key to testing exotic production modes and understanding discrepancies
- Could be the initial, powerful signature of new physics present in current data